



# Single Sludge Nitrogen Removal Systems

## Research Report No. 88

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Research Program for the Abatement of Municipal Pollution  
under Provisions of the Canada-Ontario Agreement  
on Great Lakes Water Quality

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SINGLE SLUDGE NITROGEN REMOVAL SYSTEMS

by

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## ABSTRACT

The need for nitrogen control in the treatment of wastewater has been well documented in numerous reports and papers. Rational design approaches have been developed for nitrification in combined and separate activated sludge systems and for denitrification in separate sludge systems receiving an external carbon and energy source. Recent attention has been focused on single sludge systems which combine the processes of carbon oxidation, nitrification, and denitrification in one or more reactors without intermediate clarification and with or without the addition of an external carbon source.

In this study, five different single sludge process configurations were studied at the pilot scale level. The effects of temperature, the aerobic to anoxic retention time ratio, the organic and inorganic loading conditions, the influent wastewater carbon to nitrogen ratio, and various other factors influencing nitrification and denitrification in single sludge systems were examined.

The results indicate that the critical factor affecting nitrification in single sludge systems is the aerobic solids retention time. The temperature influence upon nitrification in aerobic-anoxic systems and in purely aerobic systems appears to be comparable.

The denitrification rates in single sludge systems will depend on whether the reaction proceeds under non-carbon limiting or carbon limiting conditions. The organic carbon requirements in single sludge and separate sludge post-denitrification systems, to ensure no carbon limitation on the denitrification rate, are similar. In single sludge pre-denitrification and step-feed denitrification systems, the organic carbon requirements will be significantly greater.

Depending on the single sludge process configuration, the maximum effluent quality attainable in single sludge systems will be 2 to 3 mg/L of total N.

## RÉSUMÉ

De nombreux rapports et documents ont traité de la nécessité d'épurer l'azote des eaux usées. Les méthodes mises au point permettent la nitrification en systèmes combinés et séparés d'épuration par boues activées et la dénitrification en systèmes séparés nécessitant un apport de carbone et d'énergie. On s'est intéressé récemment aux systèmes à type unique de boues qui rendent possible l'oxydation du carbone, la nitrification et la dénitrification au moyen d'un ou de plusieurs réacteurs, avec ou sans apport de carbone, et sans qu'une clarification intermédiaire soit nécessaire.

La présente étude a permis l'examen de cinq systèmes différents à type unique de boues, en mode pilote. On y a noté les effets de la température, le rapport de la durée de retenue en conditions aérobies à celle de retenue en conditions anoxiques, les concentrations de matières organiques et inorganiques, le rapport carbone/azote dans les eaux brutes à traiter ainsi que divers autres facteurs influant sur la nitrification et la dénitrification.

Les résultats montrent que la durée de retenue des matières en conditions aérobies détermine la nitrification dans ces systèmes. Les effets de la température sur la nitrification sont pratiquement comparables, soit qu'elle se produise dans un système aérobie et anoxique, soit dans un système simplement aérobie.

Dans les systèmes à type unique de boues, la dénitrification dépend du caractère limitatif du carbone. Les besoins en carbone organique, servant à éviter toute limitation au cours de la post-dénitrification, sont comparables dans les systèmes à type unique de boues et dans les systèmes à boues séparées. Toutefois, ces besoins s'accroissent nettement dans les systèmes à type unique avec pré-dénitrification et dénitrification discontinue.

Selon la configuration du système à type unique de boues, on parvient à réduire la teneur en azote total des effluents à 2 ou 3 mg/L.

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The need for nitrogen control in the treatment of municipal and industrial wastewater has been well documented (U.S. EPA, 1975; Shuval and Gruener, 1977; Mirvish, 1977). Ammonia discharged from municipal and industrial waste sources can be toxic to aquatic life, serve as a plant and an algal nutrient, and exert an oxygen demand on the receiving water. Nitrate, the oxidized form of ammonia, can serve as an algal nutrient and may be a serious health hazard if it accumulates in water supplies.

Nitrogen control may involve either the nitrification of nitrogenous materials or total nitrogen removal. The latter can be accomplished by biological or physical-chemical methods. The physical unit process used most frequently for nitrogen removal has been ammonia stripping. The well documented problems associated with ammonia stripping under cold climatic conditions (U.S. EPA, 1975) will limit its application in many localities. An attractive alternative for nitrogen removal from wastewater is biological nitrification-denitrification.

Rational design approaches based on parameters derived from kinetic data have been developed for nitrification in combined and separate activated sludge systems and for denitrification in separate sludge systems receiving an external carbon and energy source (Christensen and Harremoës, 1977; U.S. EPA, 1975). Recent attention has been focused on single sludge systems which combine the processes of carbon oxidation, nitrification, and denitrification in one or more reactors without intermediate clarification and with or without the addition of an external carbon source. The elimination of intermediate clarification would reduce capital cost requirements and operating costs would be substantially reduced if an external carbon source such as methanol was not required. An additional reported advantage of certain single sludge process configurations is the ability to obtain a high degree of phosphorus removal without chemical addition (Barnard, 1974).

Although many single sludge systems have been proposed, they generally can be classified according to the carbon and energy source

relied upon in the denitrification step. The carbon and energy source will be supplied by:

- 1) external addition;
- 2) the organics present in the wastewater; and/or
- 3) the endogenous respiration of the biological sludge.

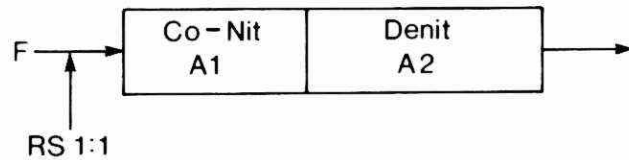
Although it has been demonstrated that for some systems high nitrogen removal can be obtained (Barnard, 1974; Christensen et al, 1977), there is a wide variation in reported results (U.S. EPA, 1975) and little kinetic rate data for the determination of the design parameter values are available and thus the development of the optimal single sludge process configuration for any given influent characteristics and environmental conditions.

There is disagreement among authors (Sutton et al, 1977a) with respect to the effects of various factors on the biological processes such as the effect of temperature on denitrification when the endogenous respiration of the biological sludge supplies the carbon and energy source (Stern and Marais, 1974) and the effect on the denitrification rate of the carbon to nitrogen ratio of the influent to the anoxic (absence of molecular oxygen) reactor. The effect of the aerobic to anoxic retention time ratio on the nitrification and denitrification rates, the degree of phosphorus removal and alkalinity consumption, the extent of sludge production, and the effluent quality which can be expected from single sludge systems are other design considerations which should be quantified. In view of the conflicting reports on the effects of various factors on single sludge systems and considering the lack of information for the design of such systems, a pilot plant study was conducted at the Wastewater Technology Centre, Canada Centre for Inland Waters, Burlington, Ontario. In this study five different single sludge process configurations were studied (Figure 1). Information was obtained for designing any single sludge system in which denitrification relied upon:

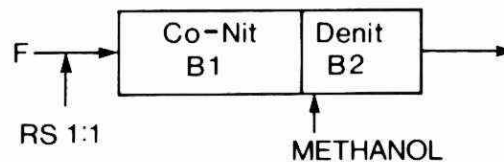
- 1) the endogenous respiration of the biological sludge (Figure 1, system A);

## CARBON OXIDATION – NITRIFICATION    POST – DENITRIFICATION

NO EXTERNAL CARBON SOURCE  
ADDITION (SYSTEM A)

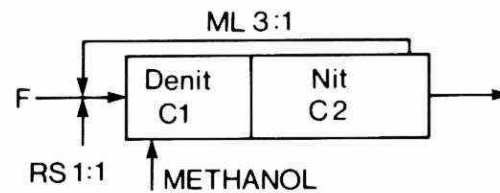


EXTERNAL CARBON SOURCE  
ADDITION (SYSTEM B)

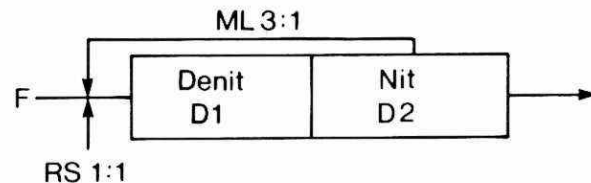


## PRE – DENITRIFICATION    NITRIFICATION

EXTERNAL CARBON SOURCE  
ADDITION (SYSTEM C)

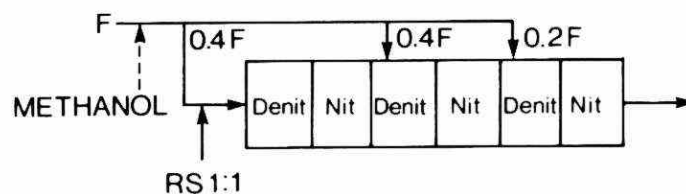


NO EXTERNAL CARBON SOURCE  
ADDITION (SYSTEM D)



## STEP – FEED    NITRIFICATION – DENITRIFICATION

(SYSTEM E)



Note: Co refers to carbon oxidation, Nit to nitrification, Denit to denitrification, F to feed, RS to return sludge, and ML to mixed liquor

FIGURE 1. SINGLE SLUDGE NITRIFICATION AND DENITRIFICATION SYSTEMS

- 2) the supply of an external carbon source (Figure 1, system B);
- 3) the organics present in the wastewater and an external carbon source (Figure 1, system C); or
- 4) the organics present in the wastewater (Figure 1, systems D and E).

The effects of temperature, the aerobic to anoxic retention time ratio, the organic and inorganic loading conditions, the influent carbon to nitrogen ratio, and various other factors influencing the nitrification and denitrification rates were quantified. In addition, information was obtained on sludge production, alkalinity consumption, phosphorus removal, and the effluent quality attainable in single sludge systems.

## 2.1 Single Sludge Process Alternatives

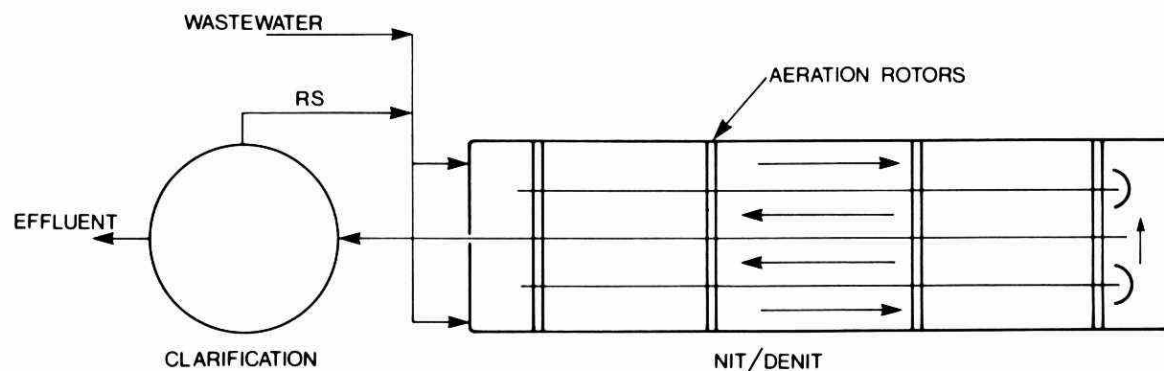
Suspended growth or activated sludge denitrification systems treating municipal wastewaters can be classified according to the carbon and energy source relied upon for nitrate respiration and on the basis of whether the reaction is carried out in a separate reactor using specific microorganisms or in a single reactor using the same microorganisms which were responsible for carbon oxidation and/or nitrification.

One of the first significant evaluations of a combined sludge nitrogen removal system was carried out by Wuhrmann (1964). The process configuration was identical to system A (Figure 1) evaluated here. Although it was established that the endogenous respiration of the biological sludge controlled the rate of denitrification, little process design information was presented. It is evident from the work of Wuhrmann (1964) and others (U.S. EPA, 1975) that the denitrification rate per mass of volatile suspended solids will be significantly less when nitrate respiration relies on the endogenous respiration of the biological sludge and not on an external organic carbon source or the organics present in the wastewater. The most recent review of endogenous nitrate respiration was presented by Beer and Wang (1977). Although little kinetic information was presented, stoichiometric equations were proposed to describe endogenous nitrate respiration and methods for reactor sizing were discussed. The U.S. EPA (1975) previously summarized the endogenous denitrification rate information available from Germany, Switzerland, the United States and the Republic of South Africa as a function of temperature. They recommended a very conservative design approach, on the basis of a wide variation in the observed rates. Stern and Marais (1974) and Christensen et al (1977) have proposed theories to account for the variation in kinetic rates observed for these systems. Stern and Marais (1974) claim that the endogenous denitrification rates will decrease with increasing system solids retention time (SRT). This seems reasonable if the rate of denitrification is controlled by the rate of organic carbon release during endogenous respiration. In an activated sludge system, the organic

carbon made available due to endogenous respiration is proportional to the number of viable organisms which decrease with increasing SRT (Stern and Marais, 1974). Christensen et al (1977) claim that in a post-denitrification system such as A (Figure 1), the SRT of the aerobic carbon oxidation-nitrification stage will determine the denitrification rate in the anoxic reactor. They claim that if the aerobic SRT is kept low enough only part of the influent organic carbon will be oxidized and yet nitrification will still be maintained. Consequently, the denitrification rate will vary between an upper limit corresponding to where the organics present in the wastewater provide the carbon and energy source, and a lower limit corresponding to where endogenous respiration controls denitrification.

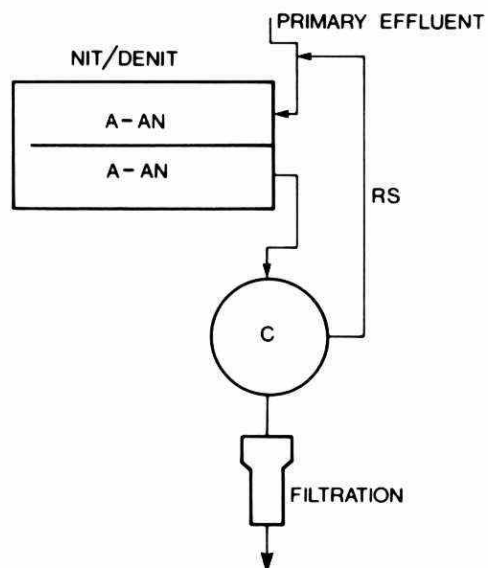
Other systems in which the denitrification rate may be expected to vary between these upper and lower limits are systems in which the wastewater is exposed to alternating aerobic-anoxic zones. The oxidation ditch can be considered as an alternating aerobic-anoxic system. The aeration rotors (Figure 2) induce cycling of the mixed liquor creating aerobic and anoxic conditions and consequently promoting nitrification and denitrification. In a large scale demonstration study in Austria (Matsché, 1977), total nitrogen removals up to 90% were achieved in a carousel oxidation ditch. The design of oxidation ditches for nitrogen removal must be conservative as it is difficult to control the reactor dissolved oxygen profile and thereby determine the length of time the wastewater is under aerobic and anoxic conditions. This problem has been overcome by using staged aerobic-anoxic processes (Figure 2). These systems have been investigated by Christensen (1975), Tholander (1977) and Bishop et al (1976). Christensen's process involved four phases and consisted of two reactors in series followed by clarification (Figure 2). The wastewater was directed between the two reactors which were either being aerated or mixed according to a predetermined sequence. In the system operated by Bishop et al (1976), the wastewater passed through two reactors in series and aerobic-anoxic conditions were achieved by alternately aerating and stirring each reactor for 30-minute intervals (Figure 2). Total nitrogen removals of over 80% were achieved in the staged processes. Although the practice

## AEROBIC-ANOXIC OXIDATION DITCH PROCESS (MATSCHÉ, 1977)

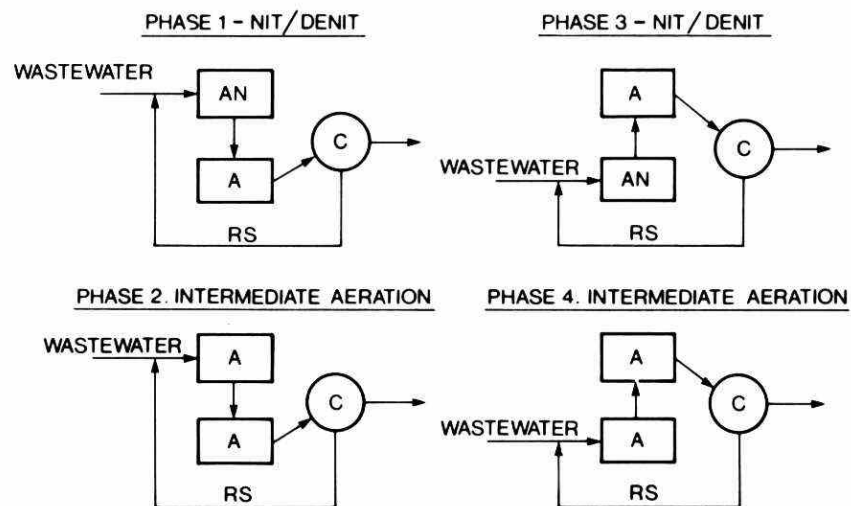


## STAGED AEROBIC-ANOXIC PROCESSES

ALTERNATING AEROBIC-ANOXIC PROCESS (BISHOP ET AL, 1976)



ALTERNATING WASTEWATER CONTACT AEROBIC-ANOXIC PROCESS (CHRISTENSEN, 1975)



Note: NIT refers to nitrification, DENIT to denitrification, RS to return sludge, A to aerobic, AN to anoxic, and C to clarification

FIGURE 2. ALTERNATING AEROBIC-ANOXIC SINGLE SLUDGE SYSTEMS

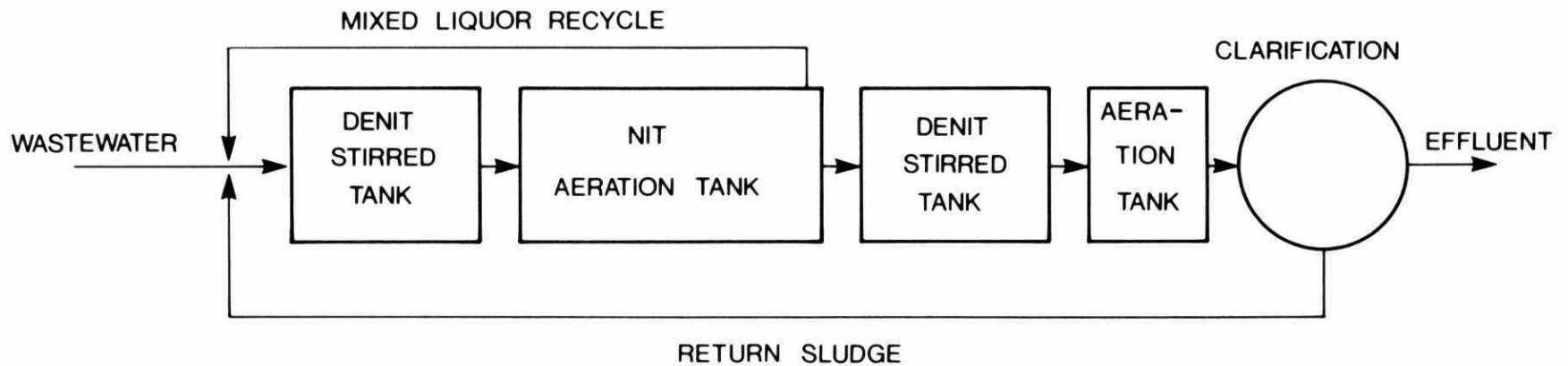


of staging allows control of the time the wastewater is under aerobic and anoxic conditions, another important design consideration is to determine at what point during the anoxic sequence the endogenous respiration of the biological sludge controls nitrate respiration. It may be expected that the value of the initial organic carbon to oxidized nitrogen ratio during any anoxic period will determine whether there is sufficient organic carbon available for the required nitrate reduction or whether endogenous respiration must be relied upon.

To ensure that nitrate respiration is not limited by endogenous respiration, an external carbon source could be added to an alternating aerobic-anoxic or a post-denitrification system. Smith (1976) and Barnard (1973) have observed high nitrate removals when methanol was added to the anoxic reactors of post-denitrification systems similar to system B (Figure 1) studied here. Wuhrmann (1957) by-passed part of the influent wastewater to the anoxic reactor of a post-denitrification system in an attempt to increase the nitrate removal rate. The principle of by-passing part of the raw sewage to an anoxic reactor was extended in this study by step-feeding to three anoxic zones in a staged alternating aerobic-anoxic system (Figure 1, system E). Recently, researchers at the Stevenage laboratory in England (Cooper et al, 1977) studied a similar configuration although feed was directed to two anoxic zones only. They achieved approximately 80% filtered nitrogen removal.

The pre-denitrification nitrification system, incorporating extensive nitrified mixed liquor recycle to the anoxic reactor (Figure 1, system D) was first studied by Ludzack and Ettinger (1962). A high degree of total nitrogen removal can be achieved provided complete denitrification and nitrification are obtained in the anoxic and aerobic reactors, respectively.

A single sludge system which has recently received much attention combines the principles of the Wuhrmann (1964) and the Ludzack and Ettinger (1962) configurations (Figure 1, systems A and D). The system is referred to as the Bardenpho process (Figure 3) and was developed in South Africa by Barnard (1974). The system relies on the organics present in the wastewater for denitrification in the first anoxic reactor and relies on endogenous respiration for denitrification



Note : DENIT refers to denitrification , and NIT to nitrification

FIGURE 3. "BARDENPHO" NITROGEN AND PHOSPHORUS REMOVAL PROCESS

in the second anoxic reactor. Although testing of full scale activated sludge systems in South Africa modified to incorporate the Bardenpho principles appears to confirm Barnard's results (Nicholls, 1977), the lack of sufficient kinetic rate data does not permit optimal design of new facilities. In addition to nitrogen removal, a high degree of phosphorus removal has been reported in the Bardenpho process (Barnard, 1974) and in modified versions of the process (Osborn and Nicholls, 1977).

Other single sludge nitrogen removal process configurations have been proposed in addition to those discussed (Christensen and Harremoës, 1977; U.S. EPA, 1975), but they can also be classified according to the carbon and energy source controlling nitrate reduction.

## 2.2 Principles and Process Kinetics

### 2.2.1 Nitrification in single sludge systems

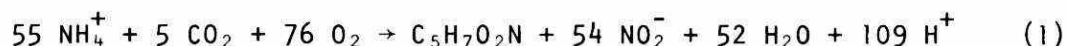
The efficiency of biological nitrogen removal is correlated to the degree of nitrification achieved. The autotrophic nitrifiers have lower yields and growth rates, and are more sensitive to environmental conditions than the heterotrophic denitrifiers. Consequently, nitrification probably will prove to be the crucial step in a single sludge nitrification and denitrification process.

Biological oxidation of inorganic nitrogen is almost entirely carried out in the aquatic environment by bacteria belonging to the family Nitrobacteraceae. The major well defined autotrophic bacteria which are known to oxidize ammonia to nitrite are the genera Nitrosomonas and Nitrosococcus. The genera Nitrobacter and Nitrocystis have been shown to oxidize nitrite to nitrate.

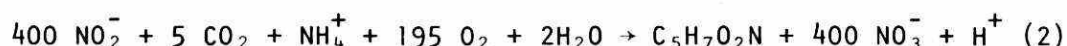
The autotrophic nitrifying organisms derive all their energy requirements for growth and cellular metabolism from the free energy released by the oxidation of an inorganic nitrogen substrate. The source of carbon used for growth is obtained from carbon dioxide or bicarbonate. The bacterial oxidation reactions of ammonium to nitrite, and nitrite to nitrate, can be combined with equations for organism synthesis to form overall synthesis - oxidation equations by knowledge

of the yield coefficients for the nitrifying organisms. Using reported values of actual cell yields, and assuming the empirical formulation of bacterial cells is  $C_5H_7O_2N$ , the following overall mass balances have been proposed (Haug and McCarty, 1972):

Nitrosomonas



Nitrobacter



On the basis of the equations, 100 mg of ammonium-nitrogen would produce only 15 mg of Nitrosomonas and approximately 2.5 mg of Nitrobacter.

In the design of any biological nitrogen removal system, the effects of environmental and process conditions on nitrification must be considered.

Autotrophic nitrifying organisms are obligate aerobes. Numerous reports indicate that in order to ensure that dissolved oxygen (DO) is not a limiting factor in the nitrification reaction, a level not less than 2.0 mg/L must be maintained (Wuhrmann, 1963; Painter, 1977). The stoichiometric oxygen requirement based on the addition of equations 1 and 2 is 4.25 mg oxygen per mg of  $\text{NH}_4^+\text{-N}$  oxidized.

Nitrification, like most bacterial processes, is affected by pH conditions. Generally, optimum conditions have been found to exist between 8.0 and 9.0 (U.S. EPA, 1975). Since the nitrification reaction produces hydrogen ions (equations 1 and 2), the alkalinity of the waste is an important consideration. Assuming the reactor pH is less than 8.5, the hydrogen ions produced during nitrification react with the bicarbonate in the wastewater, resulting in an increase in  $\text{CO}_2$  concentration and a decrease in bicarbonate alkalinity according to:



Based upon equation 3 and the addition of equations 1 and 2, 7.2 mg of bicarbonate alkalinity, expressed as  $\text{CaCO}_3$ , are required to neutralize the hydrogen ions produced during the oxidation of 1 mg of ammonia-nitrogen. Because biological nitrate reduction or denitrification consumes hydrogen ions, combining the processes using a single sludge system tends to maintain a neutral pH (Barnard, 1974).

The process of nitrification is a function of temperature within the range of approximately  $4^\circ$  to  $45^\circ\text{C}$ . The optimum for Nitrosomonas is about  $35^\circ\text{C}$  (Buswell et al, 1954) and for Nitrobacter,  $35^\circ$  to  $42^\circ\text{C}$  (Deppe and Engel, 1960; Laudelout and van Tichelen, 1960; U.S. EPA, 1975). For many reactions the variation of rate with temperature may be represented by an Arrhenius relationship. This relationship can be expressed as:

$$K_{T'} = Ae^{-E/RT'} \quad (4)$$

where:  $K_{T'}$  = reaction rate constant at temperature  $T'$  ( $\text{day}^{-1}$ )  
 $A$  = frequency factor ( $\text{day}^{-1}$ )  
 $E$  = activation energy ( $\text{cal}\cdot\text{g}\cdot\text{mole}^{-1}$ )  
 $R$  = universal gas constant ( $\text{cal}\cdot\text{g}\cdot\text{mole}^{-1} \text{ }^\circ\text{K}^{-1}$ )  
 $T'$  = temperature ( $^\circ\text{K}$ )

A popular alternative temperature relationship is the modified Arrhenius expression which can be represented as:

$$K_T = K_{15} \theta^{T-15} \quad (5)$$

where:  $K_T$  = reaction rate constant at temperature  $T$  ( $\text{day}^{-1}$ )  
 $K_{15}$  = reaction rate constant at  $15^\circ\text{C}$  ( $\text{day}^{-1}$ )  
 $\theta$  = constant  
 $T$  = temperature ( $^\circ\text{C}$ )

Nitrifying organisms, especially Nitrosomonas, are susceptible to various inhibitors which may be present in municipal and industrial wastewaters. Authors have recently identified a number of organics and

inorganics which may affect nitrifier growth rates to various degrees (U.S. EPA, 1975; Hockenbury and Grady, 1977; Sharma and Ahlert, 1977). Considering the sensitivity of nitrifiers, exposing them to zero or low DO environments, as is the case in single sludge systems, may affect their growth rates.

The Monod equation has been most often used (U.S. EPA, 1975) to describe the growth of nitrifiers and substrate removal under "steady-state" conditions. In the nitrification process the growth of Nitrosomonas and Nitrobacter are limited by the concentration of ammonia and nitrite, respectively. Since the maximum growth rate of Nitrobacter is greater than the maximum growth rate of Nitrosomonas, the rate limiting step in the nitrification reaction is the conversion of ammonia to nitrite. Using the Monod expression, the growth rate of Nitrosomonas (NS) is given by:

$$U_{NS} = U_{NS}^* \frac{A}{C_A + A} \quad (6)$$

where:  $U_{NS}$  = growth rate of NS ( $\text{days}^{-1}$ )  
 $U_{NS}^*$  = maximum growth rate of NS ( $\text{days}^{-1}$ )  
 $A$  =  $\text{NH}_4^+$ -N concentration ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $C_A$  = A at which  $U_{NS} = 0.5 U_{NS}^*$  ( $\text{mg} \cdot \text{L}^{-1}$ )

The oxidation of ammonia can be related to the NS growth rate according to:

$$\frac{1}{X_{NS}} \frac{dA}{dt} = \frac{U_{NS}}{Y'_{NS}} = K_A = K_A^* \frac{A}{C_A + A} \quad (7)$$

where:  $X_{NS}$  = NS mixed liquor volatile suspended solids concentration ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $K_A$  = ammonia oxidation rate ( $\text{mg} \cdot \text{mg}^{-1} \cdot \text{day}^{-1}$ )  
 $K_A^*$  = maximum ammonia oxidation rate ( $\text{mg} \cdot \text{mg}^{-1} \cdot \text{day}^{-1}$ )  
 $C_A$  = A at which  $K_A = 0.5 K_A^*$  ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $Y'_{NS}$  = NS net yield coefficient ( $\text{mg} \cdot \text{mg}^{-1}$ )

The net yield coefficient for NS can be considered equal to the actual yield coefficient ( $Y_{NS}$ ) as the endogenous decay coefficient is negligible (Downing et al, 1964). Equation 7 indicates a zero order relationship between the oxidation rate and substrate concentration when the value of  $C_A$  is much less than  $A$ . The zero order nature of the nitrification reaction down to low ammonia-nitrogen concentrations (1 to 3 mg/L) has been reported by numerous authors in the treatment of municipal wastewater (Kiff, 1975; Heidman, 1975; Downing et al, 1964).

The growth of microorganisms may be expressed in terms of their doubling or generation time. Generation times of heterotrophic bacteria, those responsible for carbonaceous oxidation or BOD removal, are normally reported as 10 to 20 times greater than the generation times for nitrifiers (Lawrence and McCarty, 1970). In the activated sludge system a direct consequence of the slow growth rate or long generation time of nitrifiers is the requirement of a sufficient SRT or sludge age to retain an adequate population of these organisms. In an activated sludge system the SRT is normally defined as:

$$SRT = \frac{\text{total mixed liquor suspended solids in reactors}}{\text{solids lost in effluent and through sludge wasting} \cdot \text{day}^{-1}} \quad (8)$$

At equilibrium, the solids lost or intentionally wasted will be equal to the solids produced. Therefore, the growth rate ( $U$ ) and SRT ( $\theta$ ) of all organisms in an activated sludge system are related by:

$$U = \frac{1}{SRT} = \frac{1}{\theta} \quad (9)$$

Consequently, the growth rate of Nitrosomonas is fixed according to the system SRT. If it is assumed in a single sludge nitrification and denitrification system that nitrifier growth occurs only under aerobic conditions, then the growth rate will be defined according to:

$$U_{NS} = \frac{1}{\theta_1} \quad (10)$$

where:  $\theta_1$  = aerobic SRT =  $n_1 \theta$  (days)  
 $n_1$  = mixed liquor suspended solids under aerobic conditions divided by the total mixed liquor suspended solids in reactors

Equation 10 together with equation 6 imply that there is a minimum or critical aerobic SRT at which nitrification will occur corresponding to the maximum growth rate of Nitrosomonas.

An alternative approach to defining the critical aerobic SRT for design purposes would be to determine the ammonia oxidation rate ( $K_A$ ). The relationship describing the oxidation of ammonia (equation 7) reduces to a constant ( $K_A^*$ ) if the nitrification reaction is considered to be zero order according to:

$$\frac{1}{X_{NS}} \frac{dA}{dt} = K_A^* \quad (11)$$

Equation 11 represents a simplified relationship for design provided  $X_{NS}$  can be determined. In designing single sludge systems, an estimate of  $X_{NS}$  can be made by knowledge of the ratio of the influent biodegradable organic carbon and ammonia, and the active total volatile suspended solids (X). The influent biodegradable organic carbon includes any external carbon source which may be added to promote nitrate reduction in the denitrification step. The active total volatile suspended solids can be estimated by using net yield coefficients for heterotrophic and nitrifier growth (U.S. EPA, 1975) or by using a more rigorous approach as proposed by Marais and Ekama (1976). Neglecting the inert volatile suspended solids in the influent they proposed the following relationship for the active total volatile suspended solids:

$$X = \frac{1}{1 + 0.2b\theta} X_M \quad (12)$$

where:  $b$  = organism decay coefficient ( $\text{day}^{-1}$ )  
 $= 0.10 (1.03)^{T-20}$  (Eckenfelder, 1975)  
 $X_M$  = measured total volatile suspended solids concentration  
 $(\text{mg} \cdot \text{L}^{-1})$



$X_{NS}$  can then be estimated from:

$$X_{NS} = \frac{Y_{NS} (A_o - A)}{Y_{NS} (A_o - A) + Y_H (S_o - S)} X \quad (13)$$

where:  $A_o - A = \text{NH}_4^+ - \text{N}$  nitrified ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $S_o - S =$  organic carbon consumed for aerobic and nitrate respiration ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $Y_{NS} =$  NS yield coefficient ( $\text{mg} \cdot \text{mg}^{-1}$ )  
 $Y_H =$  heterotroph yield coefficient ( $\text{mg} \cdot \text{mg}^{-1}$ )

Equation 13 neglects the concentration of Nitrobacter present as the yield coefficient for these organisms is negligible compared to NS and the heterotrophic organisms. The effect of the ratio of the influent biodegradable organic carbon and ammonia on  $X_{NS}$  has been shown for single sludge aerobic systems in which only carbon oxidation and nitrification were occurring (U.S. EPA, 1975). Wide variations in the values for the maximum ammonia oxidation rate based on the total volatile suspended solids ( $K_{AV}^*$ ) under similar environmental conditions (temperature, pH, etc.) were related to differences in the wastewater BOD to ammonia ratio (U.S. EPA, 1975).

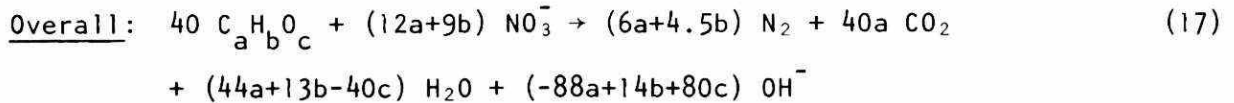
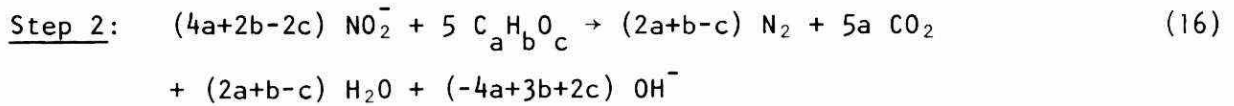
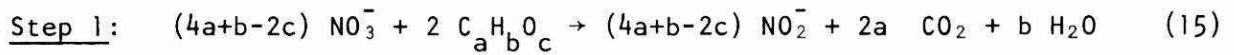
The critical aerobic SRT for nitrification can be determined from knowledge of the maximum ammonia oxidation rate through equations 7 and 10. Combining these equations leads to:

$$\theta_{1c} = \frac{1}{Y_{NS} K_{AV}^*} \quad (14)$$

## 2.2.2 Denitrification in single sludge systems

Biological denitrification is achieved under anoxic conditions by heterotrophic microorganisms that utilize nitrate as a hydrogen acceptor when an organic energy source is available. A wide variety of common facultative bacteria such as Pseudomonas, Micrococcus, Achromobacter, Spirillum and Bacillus have been reported to accomplish denitrification (Delwiche, 1956).

The reduction of nitrate occurs through a series of complicated enzyme catalyzed reactions which can follow either the assimilatory or dissimilatory route. In assimilatory denitrification, nitrate is reduced to ammonia that is used in cell synthesis. In dissimilatory denitrification, in the absence of molecular oxygen, nitrate serves as the hydrogen acceptor in the oxidation of the carbon substrate producing energy for cell growth. The gaseous end products of the reactions are principally dinitrogen ( $N_2$ ). Considering denitrification as a two-step process, the dissimilative reduction equations can be written in a general form by considering  $C_a H_b O_c$  as the carbon substrate:



In oxygen respiration the same series of reversible enzymatic reactions are involved in transferring electrons from organic substrates to molecular oxygen. It is not surprising that a wide range of aerobic activated sludge organisms (Dawson and Murphy, 1972) are capable of nitrate respiration considering the similarity in reduction pathways. Only a different terminal enzyme is required for nitrate respiration and this is formed by the bacteria in the absence of oxygen. Consequently, nitrate dissimilation is inhibited by oxygen. Oxygen respiration is favoured over nitrate respiration as the use of oxygen as the final electron acceptor yields more free energy. The occurrence of denitrification under aerobic conditions, as reported by some researchers (Myers and Matsen, 1955; Schmidt and Kampf, 1962) is likely due to a dissolved oxygen gradient across the bacterial floc.

In addition to the effects of dissolved oxygen on the design and operation of denitrification reactors, other environmental factors must be considered.

The optimum pH for denitrification is usually reported at conditions near neutrality (Christensen and Harremoës, 1977; U.S. EPA, 1975). Nitrate dissimilation is a basic reaction with hydroxyl ion production increasing the alkalinity. The stoichiometric alkalinity production will be 3.6 mg of alkalinity as  $\text{CaCO}_3$  per mg of  $\text{NO}_3\text{-N}$  reduced regardless of whether the carbon and energy source is provided by endogenous respiration of the biological sludge, methanol or the organic carbon in the influent wastewater.

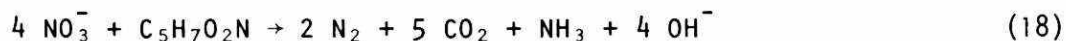
Denitrification is reported to occur over a temperature range from  $0^\circ\text{C}$  to  $50^\circ\text{C}$  with an optimum approaching  $40^\circ\text{C}$  (Christensen and Harremoës, 1977). There is reasonably good agreement between authors concerning the degree of temperature sensitivity of denitrification in activated sludge systems when an external source or the organics in the influent wastewater substrate are available as the carbon and energy source (U.S. EPA, 1975). Comparing reported temperature coefficients (U.S. EPA, 1975; Sutton et al, 1977b) denitrification, by substrate respiration, can be considered less temperature sensitive than nitrification. The variation of the denitrification rate with temperature can be represented by the Arrhenius (equation 4) or the modified Arrhenius (equation 5) expression.

Considering the sensitivity to environmental conditions of the autotrophic nitrifiers, ensuring that there are no toxicants in the wastewater limiting the nitrification rate, will also ensure that the denitrification process will be unaffected.

In single sludge post-denitrification reactors (Figure 1, reactors A2 and B2), nitrate respiration follows the processes of carbon oxidation and nitrification. Therefore, it would be expected that the residual organic carbon from the aerobic process will not be of sufficient concentration, nor in a form which is readily useable by the denitrifying population as an organic carbon and energy source. The carbon and energy source must be provided by the endogenous respiration of the

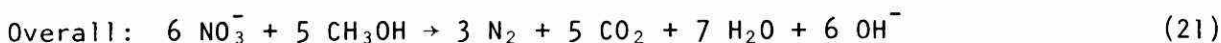
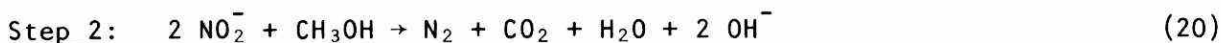
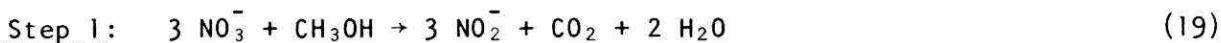
sludge, by by-passing part of the influent wastewater to the denitrification reactor, or by the addition of a carbon and energy source.

In a post-denitrification system relying on endogenous respiration of the biological sludge for nitrate reduction (Figure 1, system A), the overall stoichiometric equation can be written:

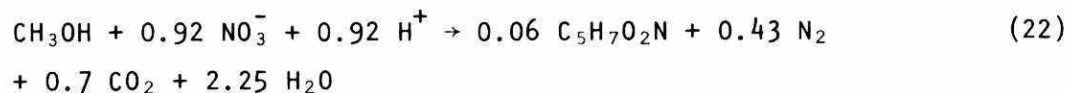


On the basis of this equation, 2 mg of biomass will be destroyed per mg of nitrate-nitrogen reduced.

In a post-denitrification reactor relying on an external carbon source (Figure 1, reactor B2), methanol will likely be the optimum choice (McCarty et al, 1969). In an industrial environment carbon-rich wastes, if available, may be attractive alternatives (Monteith, 1978). The stoichiometric nitrate reduction equations with methanol as the carbon and energy source can be written:



In addition to the methanol required for nitrate dissimilation, an amount is necessary for bacterial growth. An overall mass balance which considers this requirement is as follows (McCarty, 1973):



On the basis of this equation, 20 mg of  $\text{NO}_3\text{-N}$  would require 19 mg of  $\text{CH}_3\text{OH-C}$  and would produce 10.5 mg of bacteria. If oxygen is present, an additional amount of methanol will be required for deoxygenation according to:



Studies involving separate sludge post-denitrification reactors have determined that the methanol requirement and biomass production can be estimated from the following relationship (McCarty et al, 1969):

Methanol Requirement:

$$C_m = 2.47 N_o + 1.53 N_1 + 0.87 D_o \quad (24)$$

Biomass Production:

$$C_b = 0.53 N_o + 0.32 N_1 + 0.19 D_o \quad (25)$$

where:  $C_m$  = required methanol ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $C_b$  = biomass production ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $N_o$  = initial  $\text{NO}_3\text{-N}$  concentration ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $N_1$  = initial  $\text{NO}_2\text{-N}$  concentration ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $D_o$  = the dissolved oxygen concentration in the wastewater entering the system ( $\text{mg} \cdot \text{L}^{-1}$ )  
 (To express methanol required as COD, multiply  $C_m$  by 1.5.)

In single sludge nitrification and denitrification systems relying on the degradable organic carbon in the influent wastewater for nitrate reduction (Figure 1, systems D and E), the stoichiometric equation for the reaction can only be written if the composition of the carbon source is known. Beer and Wang (1977) presented the following equation for nitrate reduction using the composition  $\text{C}_{10}\text{H}_{19}\text{O}_3\text{N}$  for the carbon source as proposed by Christensen and McCarty (1975):



On the basis of this equation, 0.86 mg of  $\text{C}_{10}\text{H}_{19}\text{O}_3\text{N}$  as organic carbon are required for the dissimilation of 1 mg of  $\text{NO}_3\text{-N}$ . This compares with 0.72 mg of  $\text{CH}_3\text{OH}$  as organic carbon required for the nitrate-nitrogen reduction, on the basis of equation 21.

In the growth of the heterotrophic organisms responsible for denitrification, carbon and nitrate are the important substrates involved in the biological reaction. If the desire is to maximize the nitrate

reduction rate, then the denitrification process must be operated under conditions where carbon concentration is not limiting. It has been shown that when methanol is the carbon and energy source, no rate limitation will be observed if the concentration is in excess of that required for nitrate dissimilation and biomass production in accord with equation 24 (McCarty et al, 1969; Dawson and Murphy, 1973; U.S. EPA, 1975). Nitrate reduction will proceed at a constant rate until the carbon and energy source is depleted. At this point the reactor will be operating under carbon limiting conditions and any further nitrate reduction will rely on the organic carbon released during endogenous respiration.

Under non-carbon limiting conditions, little nitrite appearance has been observed and researchers have normally modelled the denitrifier growth rate according to:

$$U_{DN} = U_{DN}^* \frac{N}{C_N + N} \quad (27)$$

where:  $U_{DN}$  = growth rate of denitrifiers ( $\text{days}^{-1}$ )  
 $U_{DN}^*$  = maximum growth rate of denitrifiers ( $\text{days}^{-1}$ )  
 $N$  = nitrate-nitrogen concentration ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $C_N$  = N concentration at which  $U_{DN} = 0.5 U_{DN}^*$  ( $\text{mg} \cdot \text{L}^{-1}$ )

As with nitrification (equation 7), the corresponding denitrification rate ( $K_N$ ) reduces to a constant if the reaction is considered zero order with respect to nitrate concentration according to:

$$\frac{1}{X_{DN}} \frac{dN}{dt} = K_N^* \quad (28)$$

where:  $X_{DN}$  = denitrifier mixed liquor volatile suspended solids concentration ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $K_N^*$  = maximum denitrification rate ( $\text{mg} \cdot \text{mg}^{-1} \cdot \text{day}^{-1}$ )

Numerous reports have shown that the denitrification rate is independent of nitrate concentration (zero order) down to values of less than  $1.0 \text{ mg/L NO}_3^- \text{-N}$  in activated sludge systems (U.S. EPA, 1975).

In the design of separate sludge denitrification reactors under non-carbon limiting conditions, the use of a denitrification rate based on the total volatile suspended solids ( $K_{NV}^*$ ) has been the preferred approach (Christensen and Harremoës, 1977; U.S. EPA, 1975). Assuming the volatile solids in the anoxic denitrification reactor are entirely due to nitrate reduction, then  $K_{NV}^*$  equals  $K_N^*$  and  $K_N^*$  can be related to the minimum anoxic SRT required according to:

$$\frac{1}{\theta_{2c}} = Y_{DN} K_N^* - b_{DN} \quad (29)$$

where:  $\theta_{2c}$  = minimum anoxic SRT (days)  
 $Y_{DN}$  = denitrifier yield coefficient ( $\text{mg} \cdot \text{mg}^{-1}$ )  
 $b_{DN}$  = denitrifier decay coefficient ( $\text{days}^{-1}$ )

In a single sludge system, determining  $\theta_{2c}$  in this manner requires knowledge of  $X_{DN}$ . An estimate of  $X_{DN}$  can be made from:

$$X_{DN} = \frac{Y_{DN} (N_O - N)}{Y_{DN} (N_O - N) + Y_N (A_O - A) + Y_B (S_O - S')} \quad (30)$$

where:  $N_O - N$  =  $\text{NO}_3^- - \text{N}$  reduced ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $S_O - S'$  = organic carbon consumed in aerobic respiration ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $Y_B$  = heterotrophic yield coefficient for aerobic respiration ( $\text{mg} \cdot \text{mg}^{-1}$ )

Estimating  $X_{DN}$  using equation 30 assumes the heterotrophic and autotrophic organisms produced during aerobic respiration are not capable of nitrate respiration. It is more than likely that a percentage of the heterotrophic organisms, initially grown under aerobic conditions, are capable of nitrate reduction. The use of a denitrification rate based on total volatile suspended solids concentration for the design of the anoxic reactor(s) in single sludge systems is a reasonable approach provided the limitations of the method are realized. From the previous discussion it may be expected that under similar environmental conditions (temperature, pH, etc.),  $K_{NV}^*$  will vary depending on the ratio of the influent organic carbon available for aerobic respiration and the influent ammonia concentration available

for nitrification. This assumes that the system is designed for complete nitrification and denitrification. The degree of variability for  $K_{NV}^*$  may be expected to depend on the percentage of the heterotrophic organisms, initially grown under aerobic conditions, capable of nitrate reduction.

A straightforward approach for denitrification reactor design in a single sludge system is to specify the minimum or critical anoxic SRT required for denitrification. If the measured anoxic SRT ( $\theta_2$ ) is defined as:

$$\theta_2 = n_2 \theta \quad (31)$$

where:  $n_2$  = mixed liquor suspended solids under anoxic conditions divided by the total mixed liquor suspended solids in reactors

Then the point at which nitrate breakthrough occurs:

$$\theta_{2c} = \theta_2 \quad (32)$$

An estimate of  $K_N^*$  can be made from equation 29 providing  $\theta_{2c}$  equals  $\theta_2$ . This will be the case if the heterotrophic organisms capable of nitrate reduction can be grown only under anoxic conditions. Since it is likely that a percentage of the heterotrophs grown under aerobic conditions reduce nitrate,  $\theta_{2c}$  will be dependent on the influent organic carbon available for aerobic respiration.

In single or separate sludge anoxic denitrification reactors, the minimum denitrification rate will be observed under conditions where the endogenous respiration of the biological sludge releases organic carbon which then becomes available for nitrate reduction. Under these conditions the nitrate reduction rate has been reported as zero order with respect to nitrate concentration (Stern and Marais, 1974; Beer and Wang, 1977) and is normally expressed as:

$$\frac{dN}{dt} = K_{NE} X_M \quad (33)$$

where:  $K_{NE}$  = endogenous denitrification rate ( $\text{mg} \cdot \text{mg}^{-1} \cdot \text{day}^{-1}$ )  
 $X_M$  = measured total volatile suspended solids concentration ( $\text{mg} \cdot \text{L}^{-1}$ )



In an activated sludge system the organic carbon made available due to endogenous respiration is proportional to the number of viable organisms. Since the number of viable organisms decreases with increasing SRT, it can be expected that  $K_{NE}$  decreases with increasing SRT.

The filterable N removal attainable in a single sludge system will be influenced by the process configuration, even though complete nitrification and denitrification are obtained in the aerobic and anoxic reactors, respectively. Theoretically, complete removal can be obtained in a carbon oxidation-nitrification post-denitrification system relying on an external carbon source for nitrate reduction (Figure 1, system B). In a post-denitrification system relying on endogeneous respiration to supply the external carbon source (Figure 1, system A), the release of ammonia, according to equation 18, will limit nitrogen removal. In a pre-denitrification system (Figure 1, systems C and D), the filterable nitrogen removal will depend on the return sludge and mixed liquor recycle ratios (Figure 4). At the recycle ratios employed in this study (Figure 1), the theoretical filtered nitrogen removal will be 80% of the ammonia available for nitrification (Figure 4).

In a step-feed nitrification-denitrification system (Figure 1, system E), the filterable nitrogen removal will depend on the feed ratio to the final denitrification stage and on the return sludge recycle ratio. The theoretical fractional filtered nitrogen reduction can be obtained from:

$$\frac{R}{Co} = 1 - \frac{FR}{1 + RSR} \quad (34)$$

where:  $R$  = filterable available TKN for nitrification, removed ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $Co$  = ammonia nitrogen available for nitrification ( $\text{mg} \cdot \text{L}^{-1}$ )  
 $FR$  = feed ratio to the final denitrification stage  
 $RSR$  = return sludge recycle ratio

In this study, the theoretical filtered nitrogen removal will be 90% of the ammonia available for nitrification.

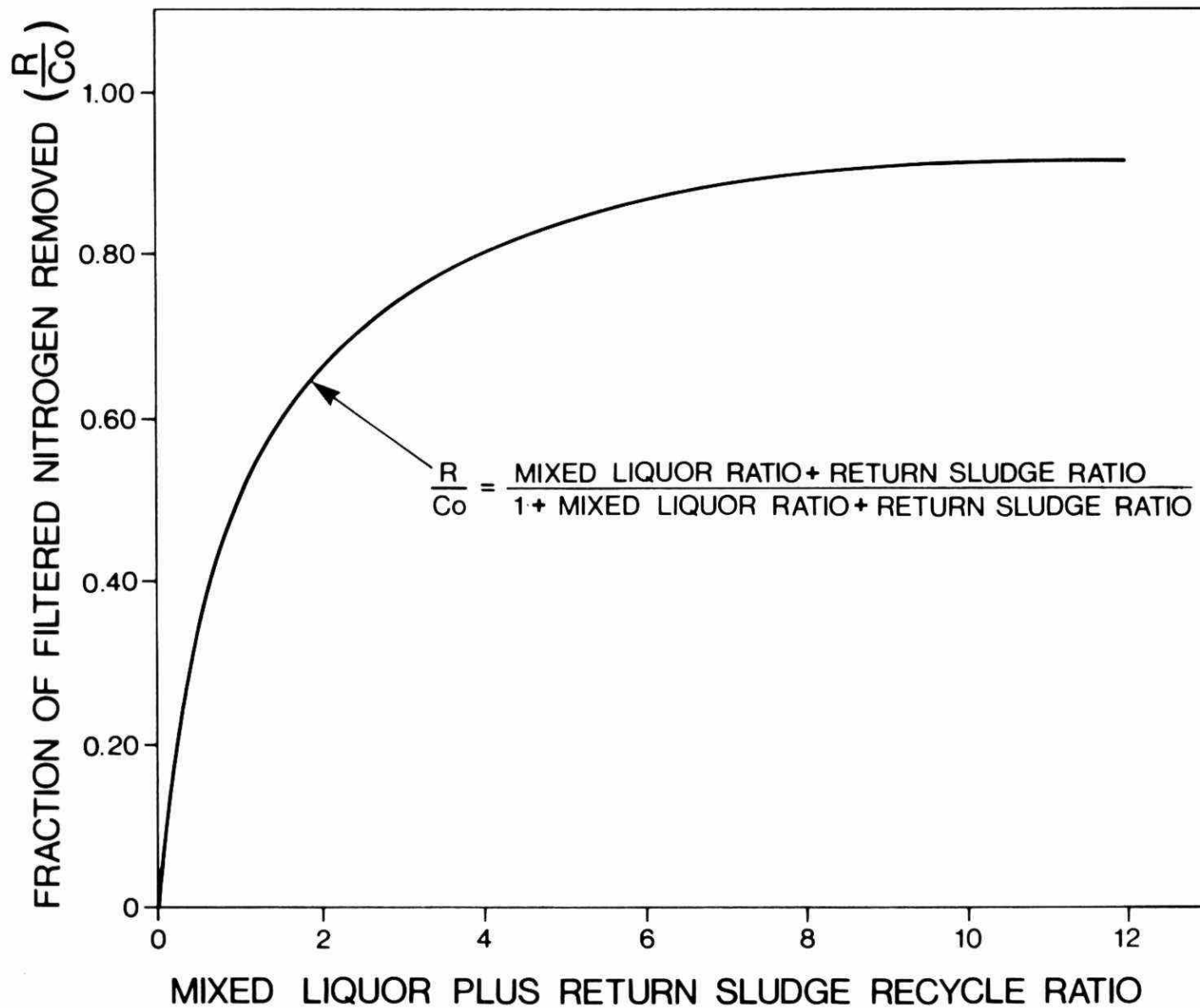


FIGURE 4. THEORETICAL FILTERED NITROGEN REMOVAL IN PRE-DENITRIFICATION NITRIFICATION SYSTEMS

### 3 EQUIPMENT AND PROCEDURES

#### 3.1 Pilot Plant Facilities and Operation

Three parallel pilot plants (Figure 5) were operated according to configurations previously discussed (Figure 1) to obtain information for the design of single sludge systems. The experimental program was divided into two phases. In Phase 1, systems A, B and C or D (Figure 1) were operated. In Phase 2, systems A, E and C or D were operated. The experimental program commenced in May 1976 and ended in June 1977. Each pilot plant biological reactor had a maximum operating capacity of  $2.18 \text{ m}^3$  (480 lgal). The reactors contained a number of removable dividers allowing operation of any one of the process configurations. The liquid volumes of the aerobic and anoxic zones could be adjusted allowing the ratio of aerobic to anoxic hydraulic retention times (HRT's) to be altered while maintaining the same system HRT.

Solid-liquid separation was achieved using upflow circular clarifiers. The clarifiers were 0.76 m (2.5 ft) in diameter. The clarifier heights could be varied between approximately 135 cm (53 in) and 102 cm (40 in) resulting in clarifier volumes between  $0.52 \text{ m}^3$  (115 lgal) and  $0.36 \text{ m}^3$  (80 lgal). The nominal HRT (HRT based on feed rate only) varied between approximately one and two hours depending on the influent feed rate and the clarifier height. Variable speed pumps delivered degrittied municipal wastewater from the Burlington Skyway Sewage Treatment Plant at a controlled temperature to each parallel system at constant flows from  $5.2$  to  $8.2 \text{ m}^3 \cdot \text{day}^{-1}$  (0.8 to 1.25 lgal) depending on the experiment in progress. The wastewater was pumped to the temperature controllers and contained normal diurnal variations in organic and inorganic concentrations (Table 1).

The performance of the systems was assessed under pseudo "steady-state" conditions (constant flow and normal diurnal variations in organic and inorganic concentrations) from analyses of composite samples derived from hour by hour sampling over a 24-hour period under equilibrium temperature and system solids retention time conditions. In operating biological systems over wide ranges of SRT's and temperature, it is important that equilibrium is obtained prior to an investigative period. In all experiments, a minimum time delay of 1.5 times the change in the anoxic and aerobic SRT, or one week per  $5^\circ\text{C}$  change in temperature, elapsed prior to an investigative period.

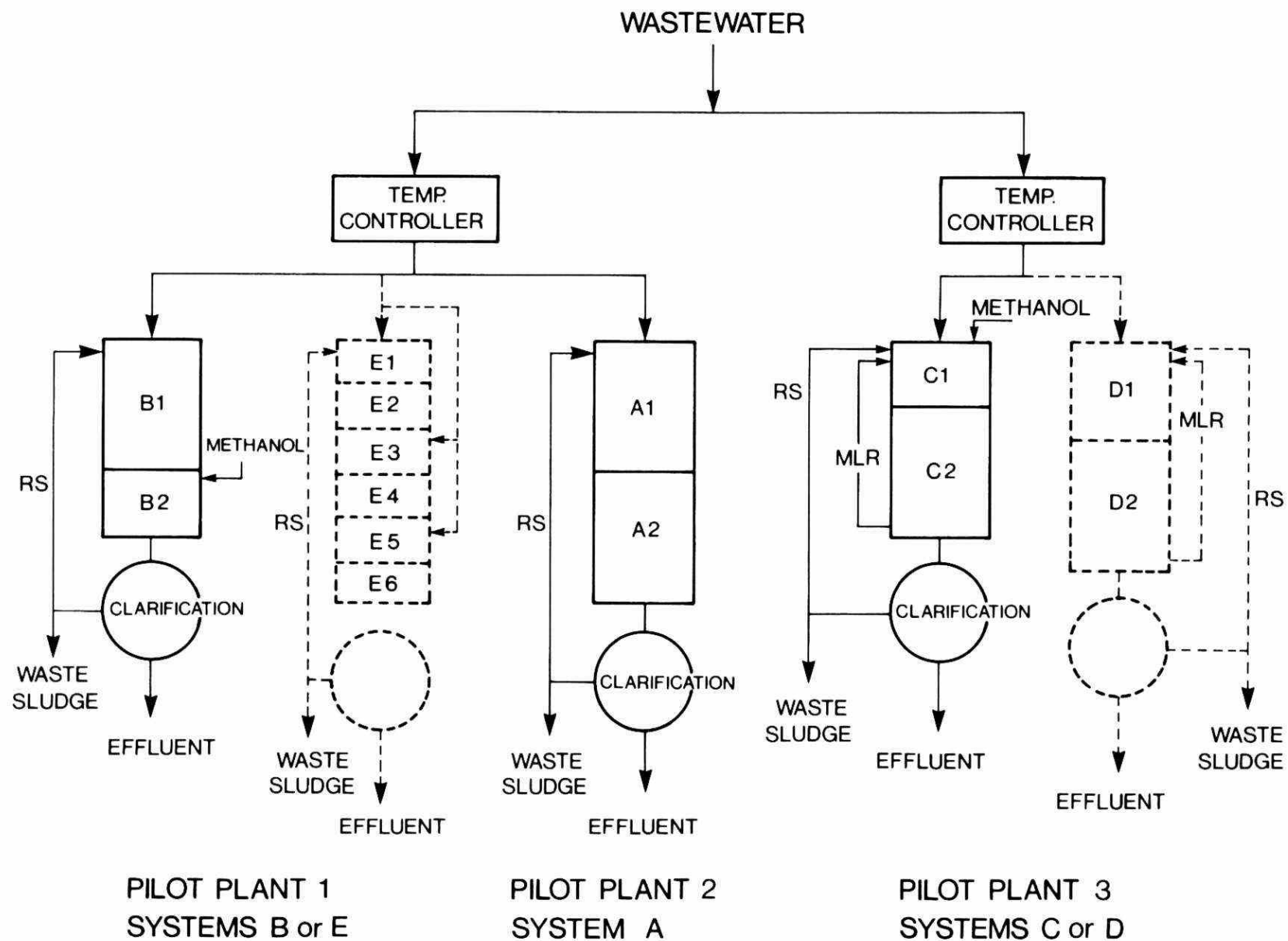


FIGURE 5. SINGLE SLUDGE PARALLEL PILOT PLANTS

TABLE 1. INFLUENT WASTEWATER CHARACTERISTICS

Characteristic $\text{mg}\cdot\text{L}^{-1}$	$\dagger$ Mean	$\ast$ 90%
COD	325	420
Filterable COD	100	134
BOD <sub>5</sub>	106	138
SS	182	244
Total P	5.2	9.4
NH <sub>4</sub> -N	17.3	21.8
Filterable TKN	20.6	25.8
Alkalinity (as CaCO <sub>3</sub> )	228	268

$\dagger$  Results based on composite of 24 hr by hr samples.

$\ast$  90% of observations are equal to or less than stated value.

The system SRT was controlled automatically by wasting from the return sludge lines. Details concerning the calculation of the SRT for the systems appear in Appendix A.

The dissolved oxygen concentration was maintained in the aerobic reactors at or above 2.0 mg/L using air diffusion. The anoxic reactors were stirred at a rate just sufficient to maintain complete mixing conditions.

### 3.2 Experimental Design

In Phase I of the experimental program, the approach was to define the system solids retention time in systems A, B and C that was necessary to achieve a given total filterable nitrogen removal at a given temperature. The experimental design involved three levels of temperature and three levels of total filterable nitrogen removal (Table 2) resulting in a complete 3 x 3 factorial design. Initially, systems A, B and C were operated at baseline ratios of aerobic to anoxic hydraulic retention times characteristic for each system (Table 3). During certain runs additional ratios above and below the baseline, but at the same system HRT, were utilized to help determine the optimum ratio of aerobic to anoxic time in each system (Table 3). During this experimental design, the addition of methanol to systems B and C was maintained at a constant rate (Appendix B, Table B1).

TABLE 2. PHASE I EXPERIMENTAL DESIGN LEVELS

Factor	System	Operating Value	Design Level
Temperature (°C)	A, B, and C	7-8	-
		14-16	0
		24-26	+
Total Filterable N Removal (mg·L <sup>-1</sup> )	A, B, and C	<10	-
		10-15	0
		>15	+

TABLE 3. PHASE I REACTOR HYDRAULIC RETENTION TIME CONDITIONS

System	Aerobic Reactor HRT, hrs		Anoxic Reactor HRT, hrs		Aerobic to Anoxic Ratio
	Nominal	Actual	Nominal	Actual	
A	4.00	2.00	6.00	3.00	Baseline (0.67)
	5.00	2.50	5.00	2.50	High (1.00)
	3.33	1.67	6.67	3.33	Low (0.50)
B	5.00	2.50	2.00	1.00	Baseline (2.50)
	5.25	2.62	1.75	0.88	High (3.00)
	4.67	2.34	2.33	1.16	Low (2.00)
C	5.00	1.00	2.00	0.40	Baseline (2.50)
	5.25	1.05	1.75	0.35	High (3.00)
	4.67	0.93	2.33	0.47	Low (2.00)
D	5.00	1.00	2.00	0.40	Baseline (2.50)

Note: Nominal HRT's based on influent flow rates, actual HRT's based on influent plus recycle flow rates.

To determine the nitrification and denitrification rates the effluent from the aerobic and anoxic reactors must contain residual  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$ , respectively. Depending on the system SRT and temperature conditions, the reactors may or may not contain these residual

concentrations under continuous operation. To supplement and verify the continuous results, batch experiments were carried out using the anoxic and aerobic reactors following the completion of experiments at the aerobic to anoxic baseline hydraulic retention time ratio. Details concerning the batch experimental procedures are contained in Appendix B.

In addition to the batch experiments and continuous runs carried out according to the experimental design, additional experiments were completed during Phase 1 on systems B and C at different methanol feed rates (Appendix B, Table B1). These experiments, together with the operation of system D, were designed to determine the effect of the influent organic carbon to nitrogen (C:N) ratio on the denitrification rate in single sludge systems.

From the results of Phase 1, the aerobic and anoxic SRT conditions necessary to obtain a high degree of total filterable nitrogen removal were estimated for system E at the three temperature levels of 7° to 8°C, 14° to 16°C and 24° to 26°C. On this basis, in Phase 2, a number of continuous runs were completed (Appendix B, Table B1). To determine the effect of the C:N ratio on the denitrification rate in system E, additional experiments were completed with methanol addition (Appendix B, Table B1) to the influent (Figure 1).

The effect of the C:N ratio on nitrate reduction in the anoxic reactor of the pre-denitrification nitrification system was assessed in Phase 2 by operating systems C and D. The SRT required to obtain complete nitrate removal in the anoxic reactor without methanol addition was determined at the 14° to 16°C temperature level by operation of a much higher anoxic HRT than the baseline condition (Table 3) or at a much lower aerobic to anoxic ratio (Appendix B, Table B1).

Experiments with system A were completed in Phase 2 at various aerobic to anoxic hydraulic retention time ratios and at anoxic HRT's (nominal) up to 8.0 hr (Appendix B, Table B1) to determine the conditions required to obtain optimum nitrogen removal at each temperature level.

In addition to the batch experiments completed in the pilot plant reactors in Phase 1, parallel batch studies using sludge derived from the anoxic reactor of the pre-denitrification nitrification systems

(Figure 1, systems C and D) were completed to compare the rate of nitrate reduction using methanol under non-carbon limiting conditions and using the organics present in the influent sewage, under non-carbon limiting and carbon limiting conditions.

### 3.3 Sample Preparation and Analyses

Samples for organic carbon were prepared by filtration through 0.3 micron Gelman glass fibre filters followed by acidification to pH 2 with concentrated hydrochloric acid. Unfiltered TKN, COD and TP samples were acidified with concentrated sulphuric acid.  $\text{NO}_3^-$ -N,  $\text{NO}_2^-$ -N, filtered TKN, TP,  $\text{NH}_3$ -N and COD were prepared for analyses by filtration through 0.3 micron Gelman glass fibre filters and frozen, together with BOD samples, while awaiting analyses.

The analytical procedures used are detailed in Appendix A.



The operating conditions and analytical results for the continuous runs of the pilot plant program have been summarized and presented in Appendix B (Tables B1 and B2). Appendix B also contains the operating and analytical results for the batch studies conducted (Tables B3, B5, B6 and B7) and a summary of the procedures followed in carrying out the batch experiments. A copy of the computer listing of the complete day to day operating and analytical results for the continuous runs of the pilot plant program can be obtained by contacting the Head, Biological Processes Unit, Wastewater Technology Centre, Box 5050, Burlington, Ontario.

The three parallel pilot plants (Figure 5), operating initially as systems A, B and D, were seeded by the addition of return sludge from a  $132 \text{ m}^3 \cdot \text{day}^{-1}$  (20 l/gpm) extended aeration plant. The extended aeration plant had originally been seeded with return sludge from the Burlington Skyway Sewage Treatment Plant.

#### 4.1 Nitrification Performance

To assess the nitrification performance of the systems, both the amount of filterable TKN and  $\text{NH}_3\text{-N}$  removal were determined. No significant difference was found between these measures of nitrification. This is illustrated in Figure 6 for one of the post-denitrification systems (system A) and one of the pre-denitrification systems (system C). The trend toward a slightly higher TKN removal in Figure 6 is due to the fact that the influent filterable TKN contains a small quantity of organic nitrogen which is converted to ammonia-N and then nitrified. A paired data comparison of the aerobic and anoxic reactor effluent results for the two post-denitrification systems (Figures 7 and 8) indicated that no change in the filterable TKN concentration occurred in the anoxic reactors of the systems allowing the nitrification performance to be based on the influent and final effluent concentrations. Since the reactors were completely mixed, the aerobic reactor effluent concentration in Figures 7 and 8 is equivalent to the concentration in the aerobic reactors.

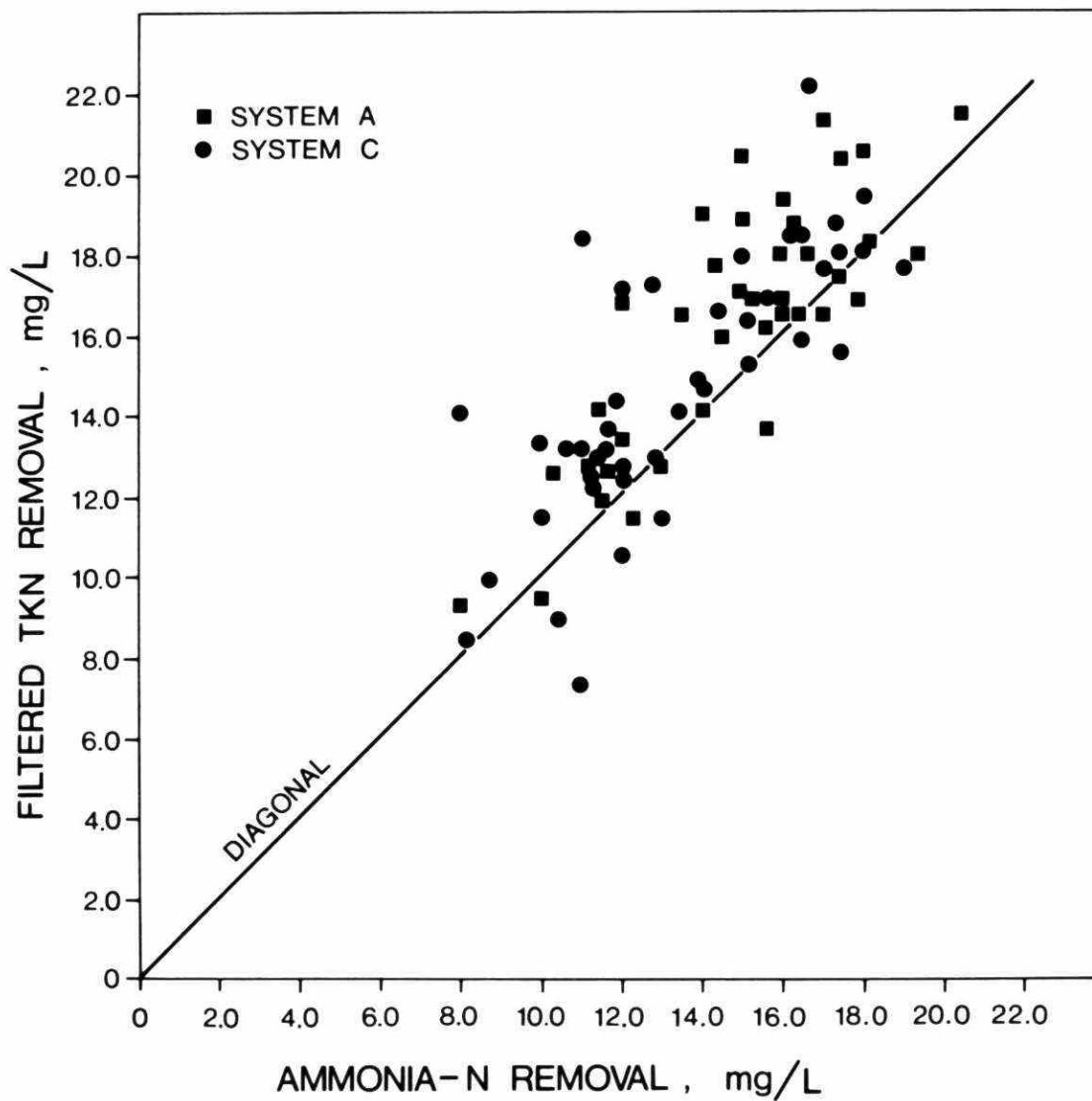


FIGURE 6. AMMONIA-N REMOVAL AND FILTERED TKN REMOVAL  
IN SINGLE SLUDGE SYSTEMS

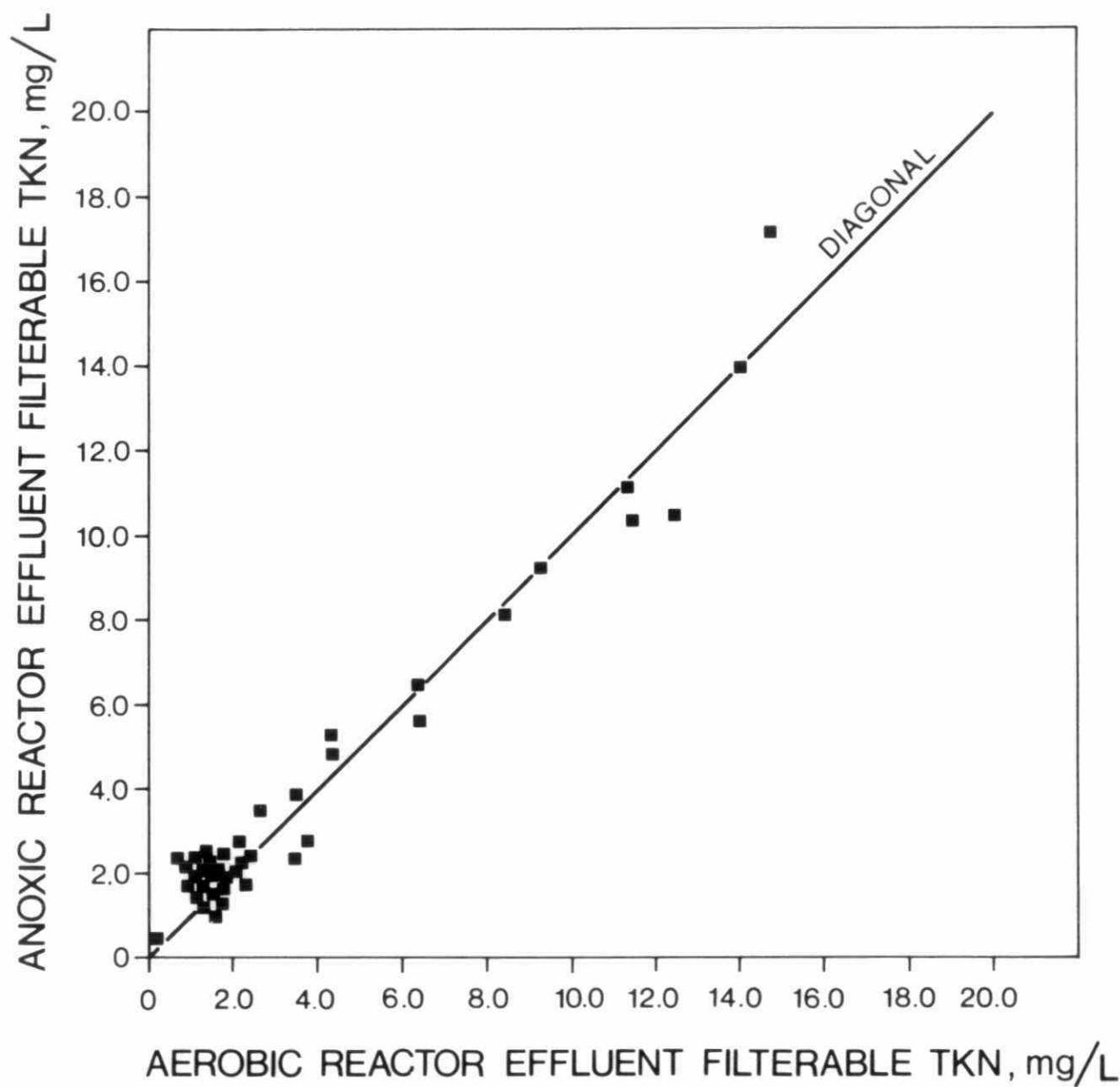


FIGURE 7. PAIRED DATA COMPARISON OF EFFLUENT FILTERABLE TKN FROM AEROBIC AND ANOXIC REACTORS OF SYSTEM A

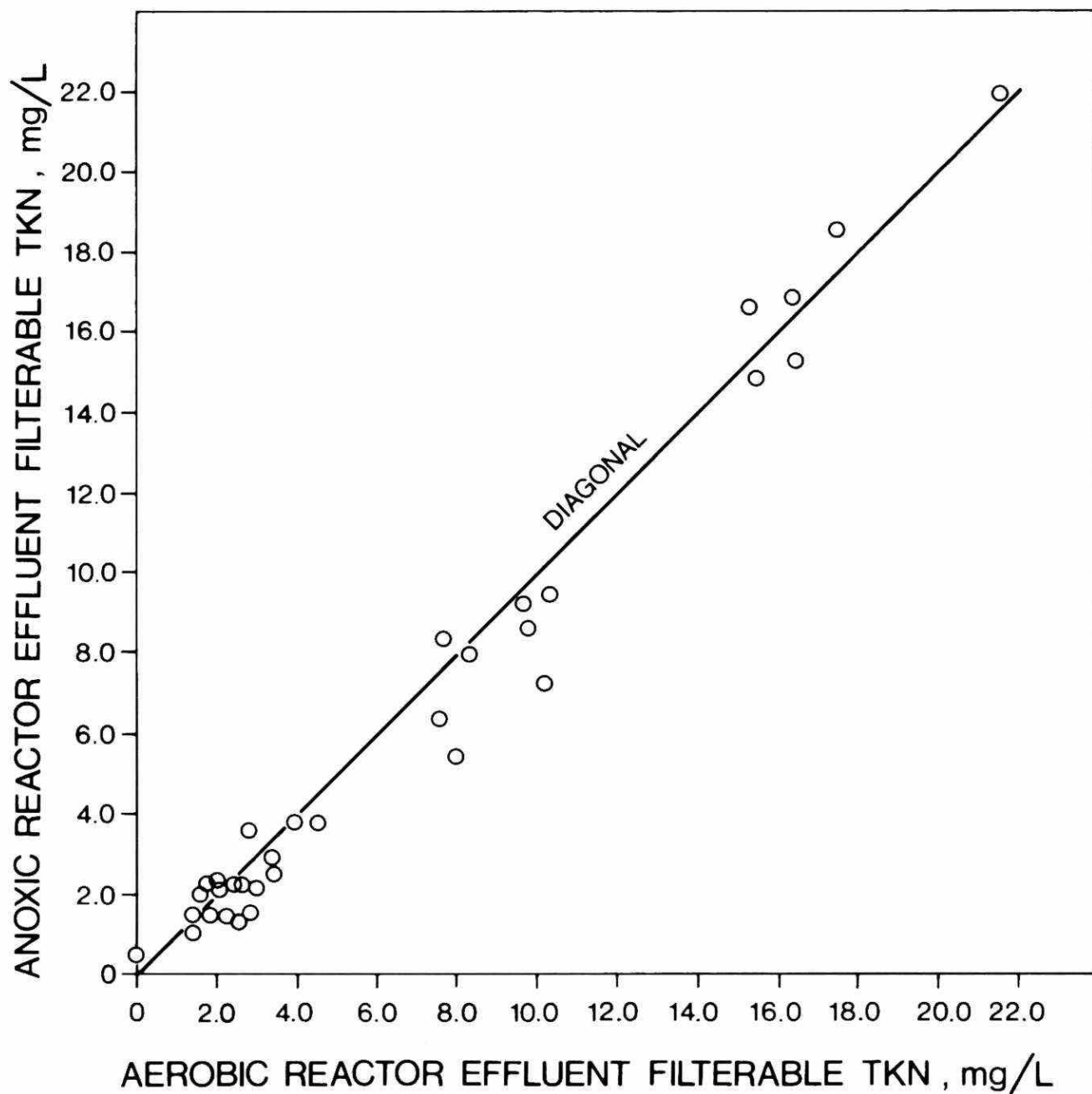


FIGURE 8. PAIRED DATA COMPARISON OF EFFLUENT FILTERABLE TKN FROM AEROBIC AND ANOXIC REACTORS OF SYSTEM B

In the aerobic-anoxic single sludge systems, the degree of nitrification was dependent on the aerobic SRT (Figure 9) indicating that nitrifier growth occurs under aerobic conditions only, in accord with the theory previously developed. Empirical relationships were used to describe the nitrification performance of the systems (Figure 9) in order to allow the results to be compared to other studies (Figure 10). The computer program used to determine the parameter values for the empirical models is presented in Appendix A, together with an example output (Table A3). The maximum percentage of filterable TKN removal (90% to 95%) was limited by the residual filterable organic nitrogen. Even with complete nitrification (ammonia-N less than or equal to 2.0), the effluents from single sludge systems can be expected to contain a mean of 1.2 mg/L of filterable organic nitrogen (Figure 11) probably associated with refractory compounds or metabolic by-products.

Under pseudo "steady-state" conditions, the variation of the influent filterable TKN concentration will affect the effluent results when the nitrification capacity is exceeded (U.S. EPA, 1975; Sutton et al, 1977c). In this study the influent peak to average filterable TKN concentration was approximately 2.0. The capacity for complete nitrification will increase as the operating aerobic SRT increases beyond the minimum necessary for nitrifier growth. The effect of the influent conditions will be more pronounced at lower temperatures as the nitrifier growth rate decreases with decreasing temperature. This accounts for the greater variation in results as the temperature level was decreased (Figure 9). The pseudo "steady-state" filterable TKN removal capacity of combined sludge aerobic carbon oxidation-nitrification systems was determined by Sutton (1976) at four, seven and ten-day SRT's over a temperature range from 5° to 25°C. The results obtained in this study compare favourably with these previous results (Figure 12). Only experimental results with effluent ammonia-N values greater than 1.0 are plotted in Figure 12 since for the determination of the maximum nitrification capacity the effluent from the reactors must contain ammonia.

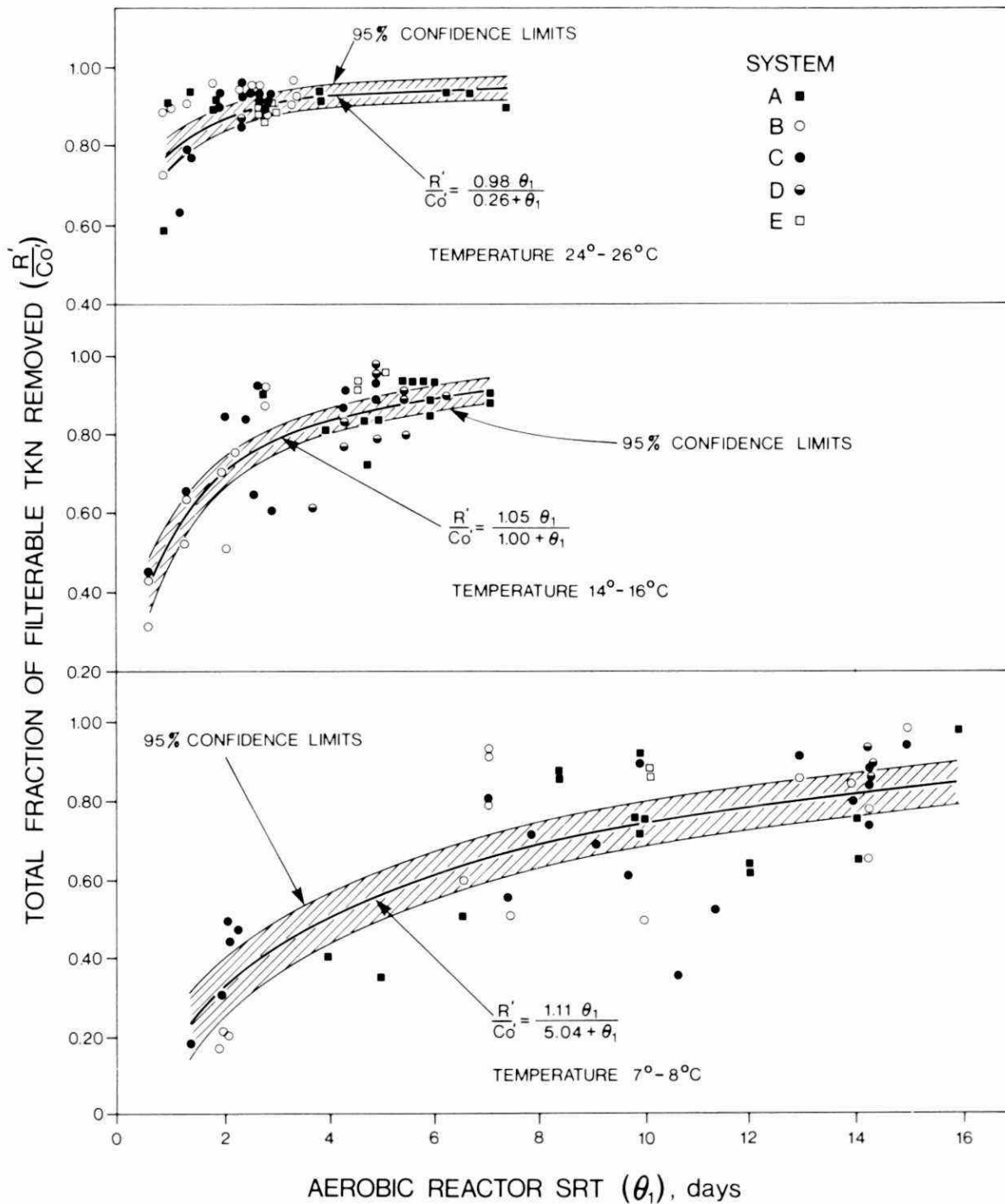


FIGURE 9. NITRIFICATION PERFORMANCE IN SINGLE SLUDGE SYSTEMS

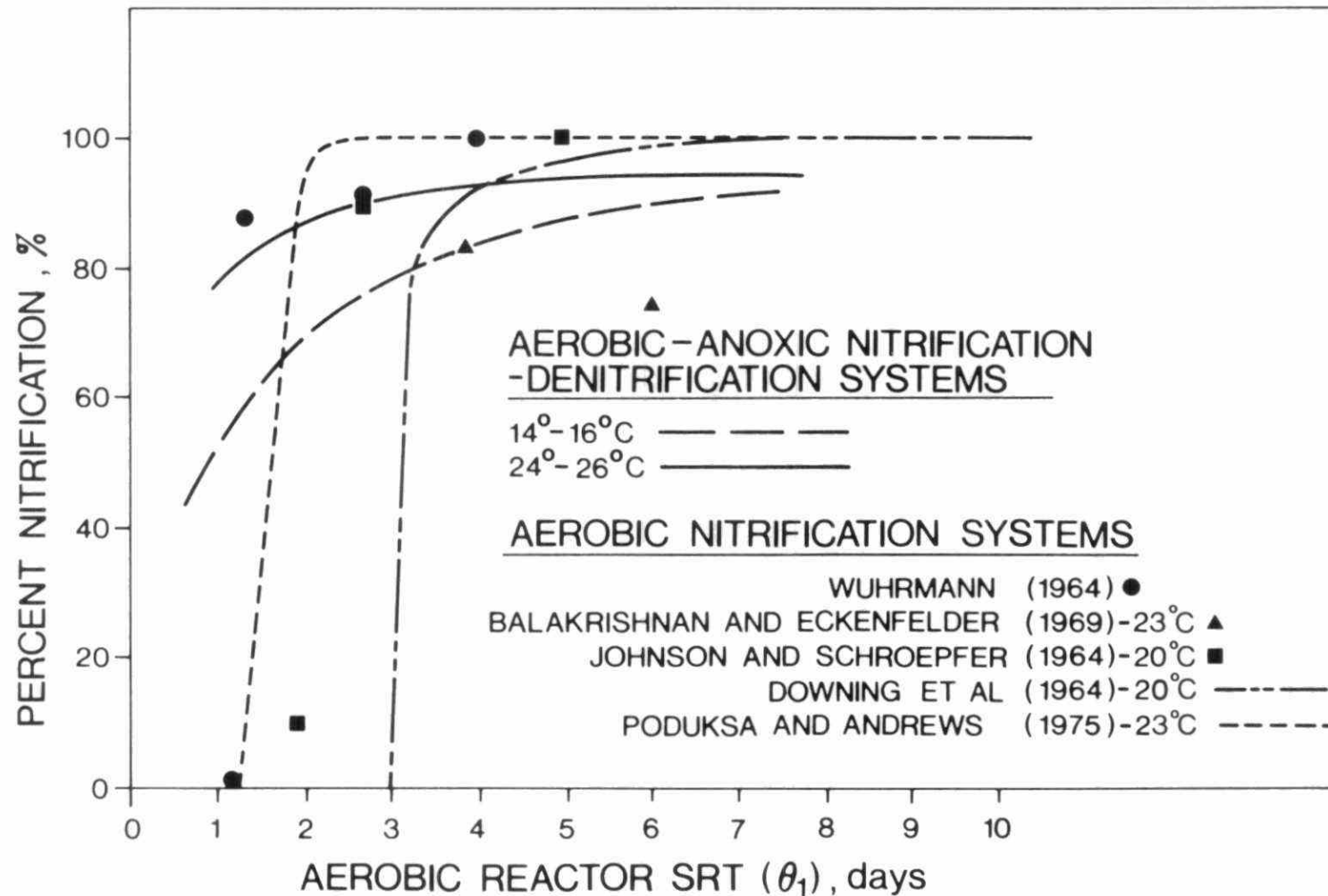


FIGURE 10. COMPARISON OF NITRIFICATION PERFORMANCE IN AEROBIC-ANOXIC SYSTEMS AND IN AEROBIC SYSTEMS

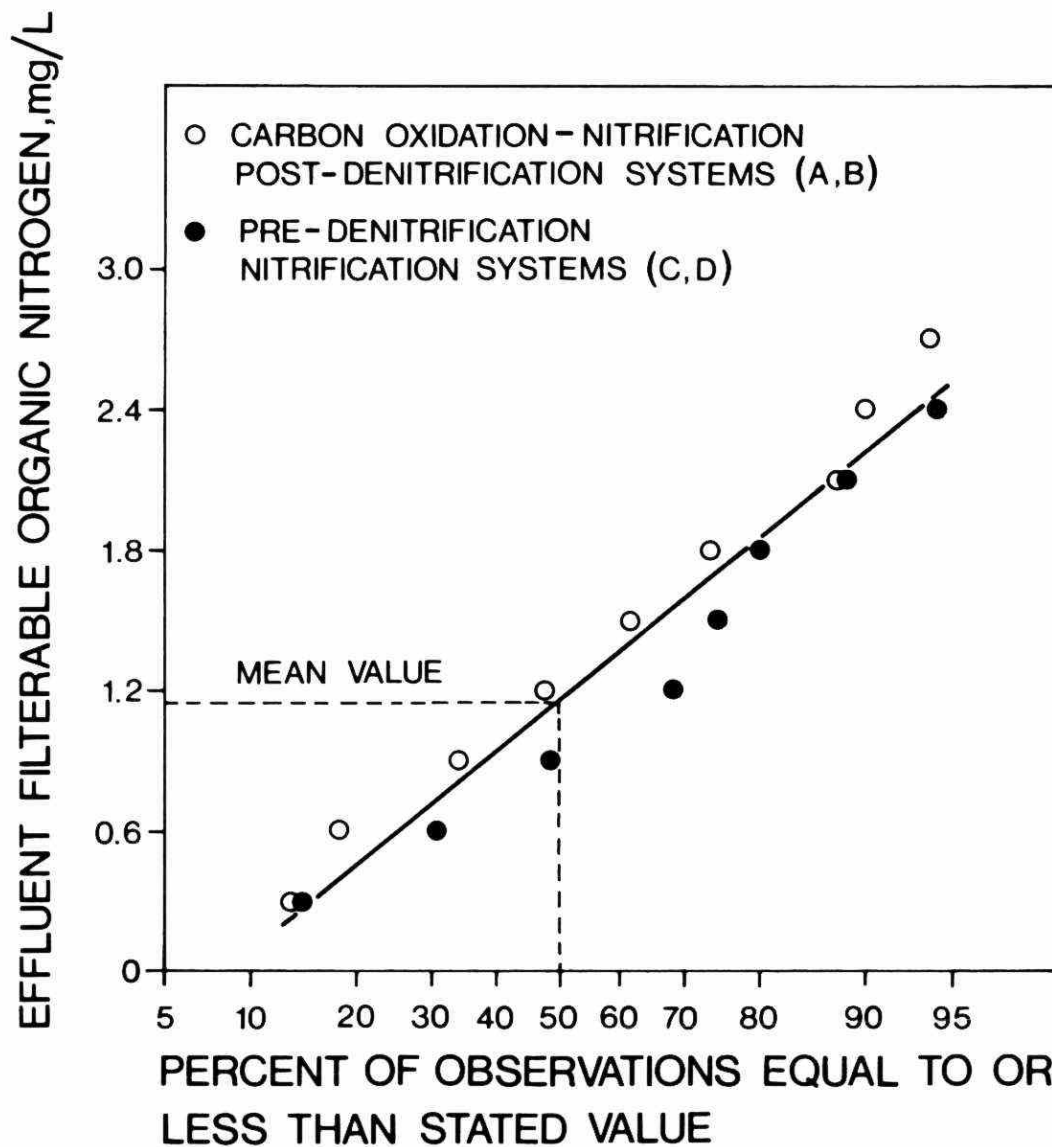


FIGURE 11. RESIDUAL ORGANIC NITROGEN FROM SINGLE SLUDGE SYSTEMS



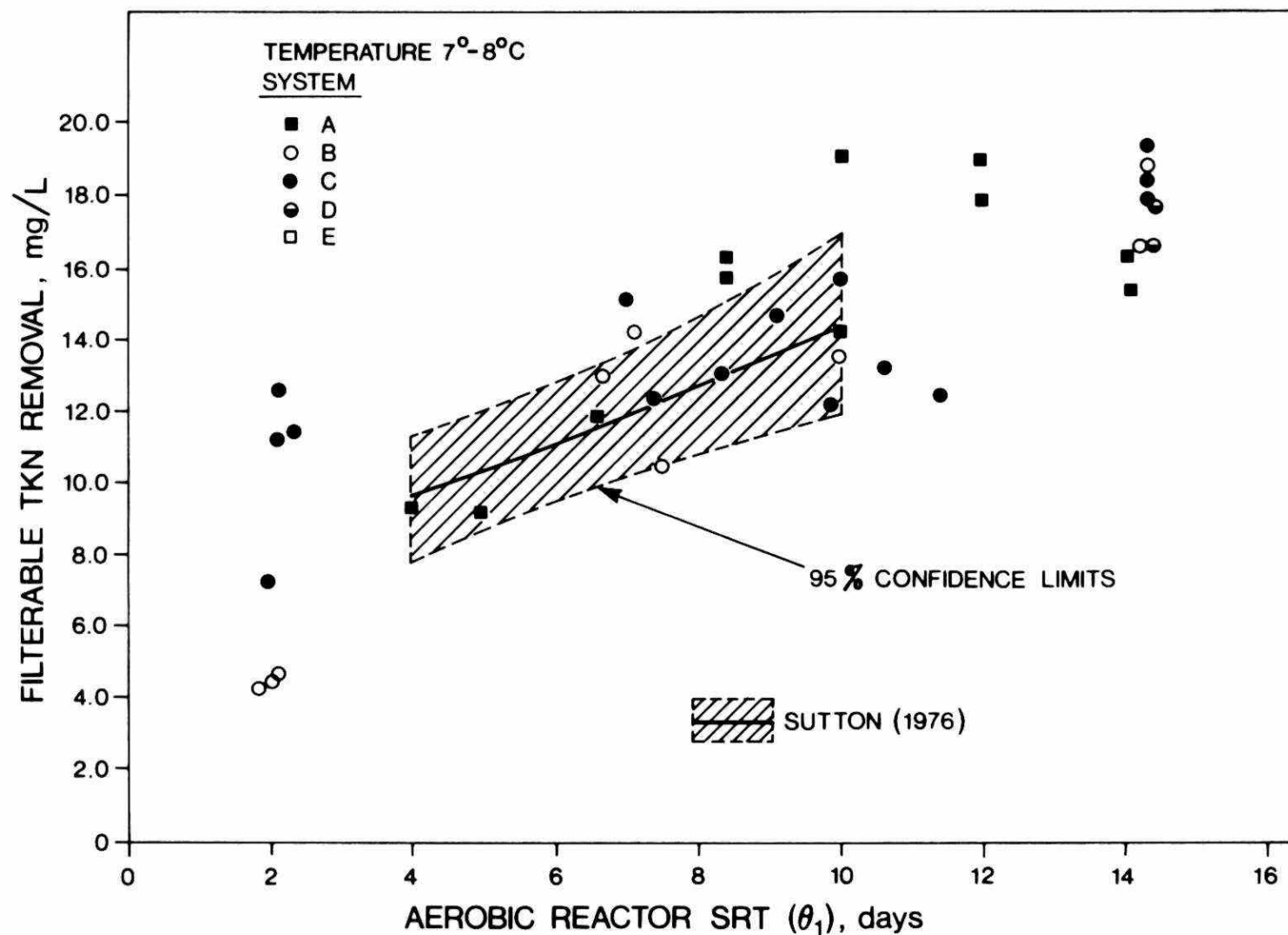


FIGURE 12. NITRIFICATION CAPACITY OF SINGLE SLUDGE SYSTEMS UNDER LOW TEMPERATURE CONDITIONS

The anoxic conditions imposed on the nitrifiers in the single sludge systems ranged from less than 0.5 hr (actual HRT) in the pre-denitrification systems (systems C and D) to 4.0 hr (actual HRT) in the post-denitrification systems (system A) with no external carbon source addition (Appendix B, Table B1). The lack of a discernable difference in the degree of nitrification in the systems at any given aerobic reactor SRT and temperature (Figure 9) supports the contention that long periods of anoxic conditions have no effect on nitrifier activity (U.S. EPA, 1975). This is in contrast to the report of Marsden and Marais (1976), who found that long anoxic periods inhibited nitrification.

The total fraction of filterable TKN removed in the systems includes that removed by nitrification plus assimilation. To determine the temperature sensitivity of the nitrifier growth rates in the systems, the empirical relationships describing the total fraction of filterable TKN removed were used together with relationships describing the fraction assimilated. The amount of filterable TKN assimilated ( $R_1$ ) was determined by operating the systems at constant SRT conditions during an investigative period and measuring the nitrogen content of the reactor volatile suspended solids. The results at 24° to 26°C are illustrated in Figure 13. Similar relationships were derived at the other temperature levels (Appendix A). An estimate of the aerobic SRT to ensure nitrification occurred was made by comparing the fraction of filterable TKN removed due to assimilation to the total fraction removed. The SRT at which the total fraction removed was twice the fraction assimilated, was defined as the SRT required for nitrification ( $\theta_1$ ). This procedure is illustrated in Figure 13 at the 24° to 26°C temperature level. Details of the calculations at the 7° to 8°C and 14° to 16°C temperature levels are presented in Appendix A. An estimate of the maximum nitrifier growth rate at each temperature level was determined from the inverse of the calculated SRT required to ensure nitrification (Table 4). The temperature sensitivity of the growth rate values was derived by fitting the results to the Arrhenius and modified Arrhenius models (Table 4). Good agreement was found between the growth rate results of the nitrifiers in the aerobic-anoxic single sludge systems and in purely aerobic nitrification systems (Figure 14).

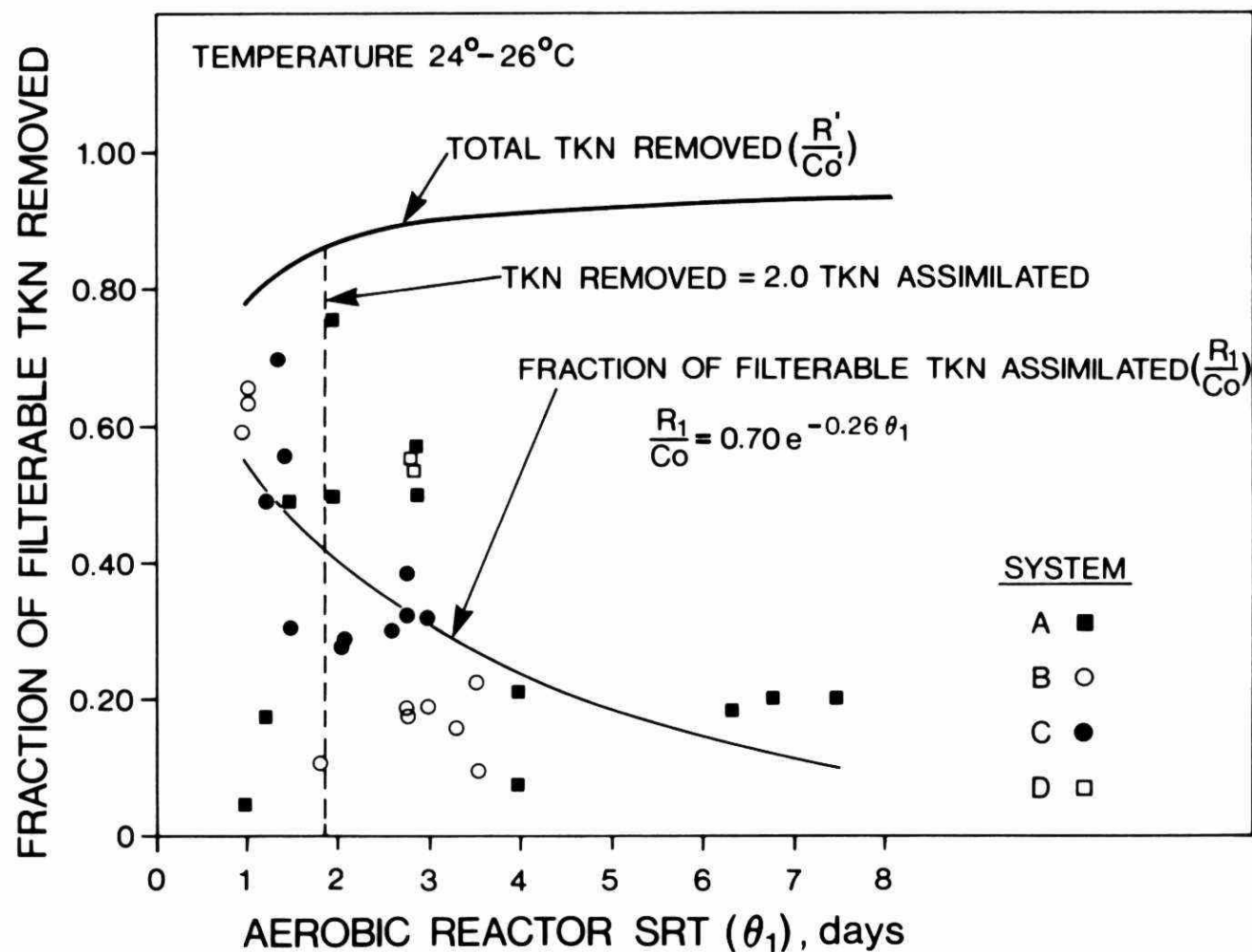


FIGURE 13. NITROGEN ASSIMILATED IN COMBINED SLUDGE SYSTEMS

TABLE 4. NITRIFICATION TEMPERATURE SENSITIVITY IN SINGLE SLUDGE SYSTEMS

Temperature Level °C	Required SRT ( $\theta_{1c}$ ) for Nitrification days	Maximum Nitrifier Growth Rate days <sup>-1</sup>	Arrhenius Model $K_T = Ae^{-E/RT}$		Modified Arrhenius Model $K_T = K_{15} \theta^{T-15}$	
			A days <sup>-1</sup>	E cal·g-mole <sup>-1</sup>	K <sub>15</sub> days <sup>-1</sup>	$\theta$
7° to 8°C	6.8	0.15	$3.48 \times 10^8$	12 000	0.27	1.073
14° to 16°C	3.2	0.31				
24° to 26°C	1.9	0.53				

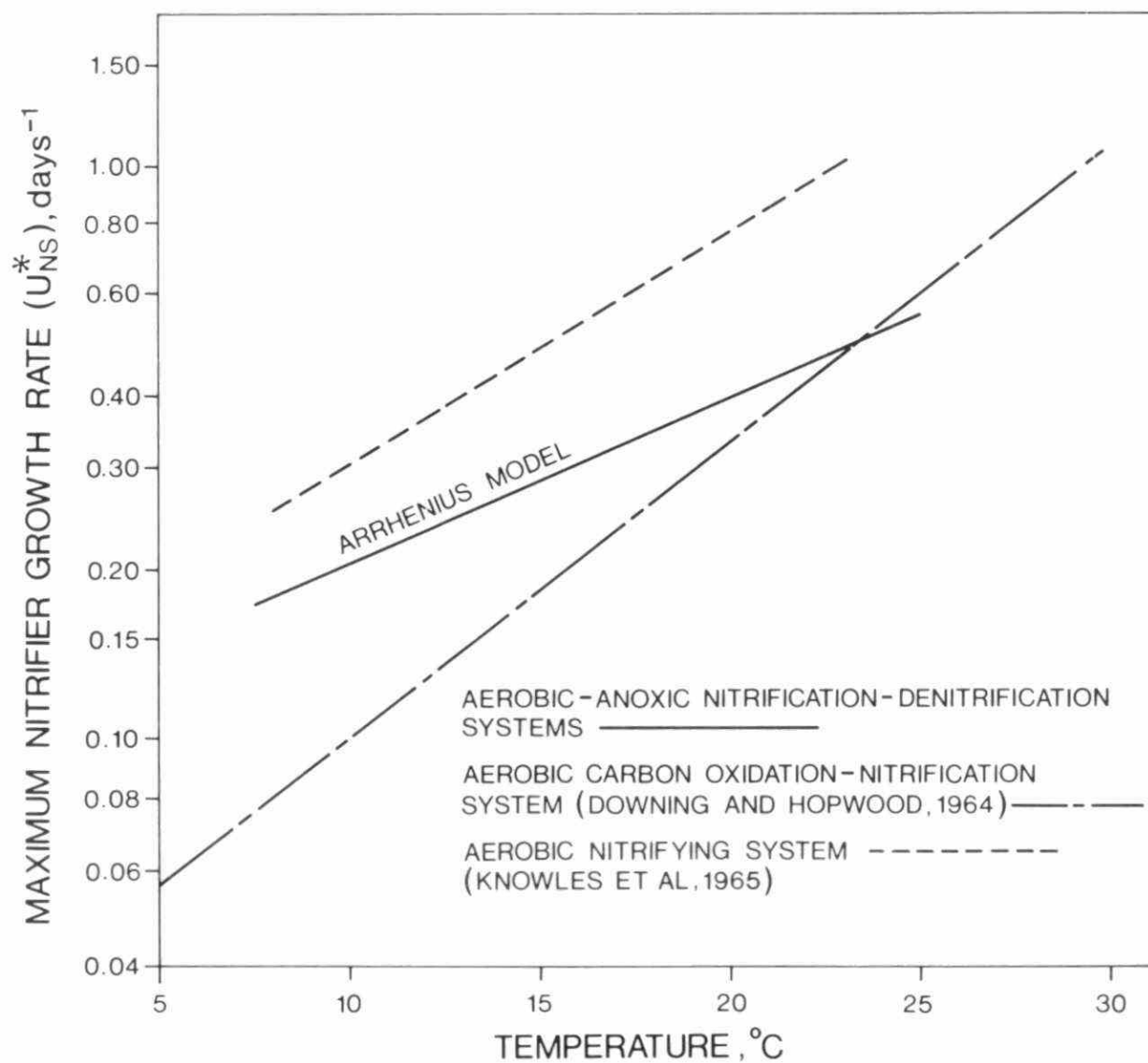


FIGURE 14. NITRIFIER GROWTH RATES IN AEROBIC-ANOXIC SYSTEMS AND IN AEROBIC SYSTEMS

The parameter values for the Arrhenius models and for the models describing the fraction of filterable TKN assimilated were determined using the computer program in Appendix A, Table A3. In computing the Arrhenius parameter values the model was first reparameterized (Sutton et al, 1975) to minimize the interaction between A and E, which makes the Arrhenius equation a difficult expression to fit.

The maximum ammonia oxidation rate ( $K_A^*$ ) can be determined from the maximum nitrifier growth rate (equations 10 and 14) through knowledge of the yield coefficient for nitrifiers ( $Y_{NS}$ ). Using the Arrhenius model results from Figure 14, the  $K_A^*$  values are recorded in Table 5. The batch nitrification experiments (Appendix B) completed in the pilot plant aerobic reactors of systems A, B and C during Phase 1, also can be used to determine  $K_A^*$ . This procedure, outlined in Appendix B, first involves determining the ammonia oxidation rates based on total volatile suspended solids ( $K_{AV}^*$ ) and then determining the volatile suspended solids associated with the NS organisms leading to the determination of  $K_A^*$  values (Figure 15).  $K_A^*$  values derived from the batch results compare favourably to those computed from Figure 14 (Table 5).

TABLE 5. MAXIMUM AMMONIA OXIDATION RATES

Temperature °C	Maximum Ammonia Oxidation Rates ( $K_A^*$ )	
	Calculated From Maximum Nitrifier Growth Rate (Figure 14) $K_A^* = \frac{U_{NS}^*}{Y_{NS}}$ $\text{mg} \cdot \text{mg}^{-1} \cdot \text{day}^{-1}$	Calculated From Batch Nitrification Results $K_A^* = 1.37 \times 10^8 e^{-10290/RT}$ $\text{mg} \cdot \text{mg}^{-1} \cdot \text{day}^{-1}$
7.5	1.07	1.32
15	1.80	2.13
24	3.40	3.65

Note: Value for  $Y_{NS}$  taken as  $0.15 \text{ mg} \cdot \text{mg}^{-1}$ .

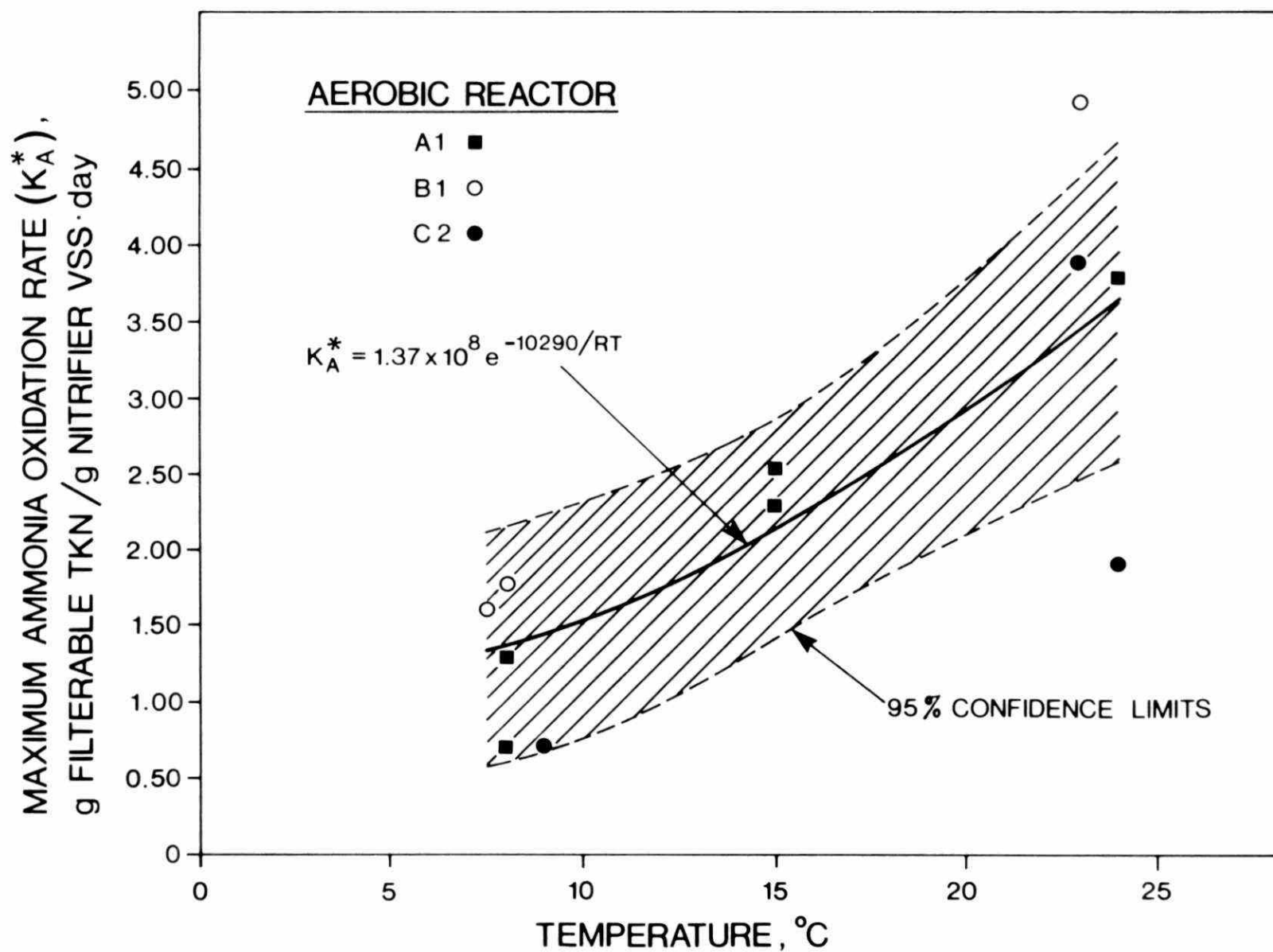


FIGURE 15. AMMONIA OXIDATION RATES DERIVED FROM BATCH NITRIFICATION RESULTS

## 4.2 Denitrification Performance

### 4.2.1 Denitrification results under non-carbon limiting conditions

In this study the results from batch experiments in the anoxic reactors of the single sludge post and pre-denitrification systems in which nitrate reduction occurred under non-carbon limiting conditions (Figure 1, reactors B2 and C1) were used to determine the maximum denitrification rates. The rates, expressed in terms of measured total volatile suspended solids ( $K_{NV}^*$ ), were determined according to the procedures detailed in Appendix B. The variation of the rates with temperature in each anoxic reactor was described by an Arrhenius relationship (Figure 16). Analysis of variance proved the individual models to be valid (Table 6).

The differences in the batch results between the post and pre-denitrification reactors (Figure 16) may be due to differences in the fraction of active denitrifiers ( $X_{DN}$ ) in the total volatile suspended solids. During the experimental phase in which the batch results were derived (Phase I), systems B and C were operated under similar anoxic ( $\theta_2$ ) and system ( $\theta$ ) SRT conditions. Consequently, the effect of SRT on the active volatile fraction, as expressed through equation 12, does not account for the difference in results. The fraction of  $X_{DN}$ , as expressed by equation 30, may be different for systems B and C if the production of organisms, other than denitrifiers, is greater in one system than the other. Examination of the Phase I continuous results indicates that the only significant difference between the performance of the system was a greater consumption in system C of organic carbon expressed as COD. The increased consumption of COD can be related to the addition point of the external carbon source. The excess organic carbon fed to the pre-denitrification reactor of system C is oxidized in the aerobic stage resulting in further biomass production. For system B, the excess organic carbon from the post-denitrification reactor passes out into the effluent. The mean COD consumption in the system in Phase I was calculated previously in determining the ammonia oxidation rates from the batch nitrification results (Appendix B). The ratio of COD consumption in system C to consumption in system B was 1.4. Comparing the batch rates from the individual Arrhenius models for reactors B2 and C1 (Figure 16), the ratio of the rate in B2 to the rate in C1 varies between 1.4 and 1.5.



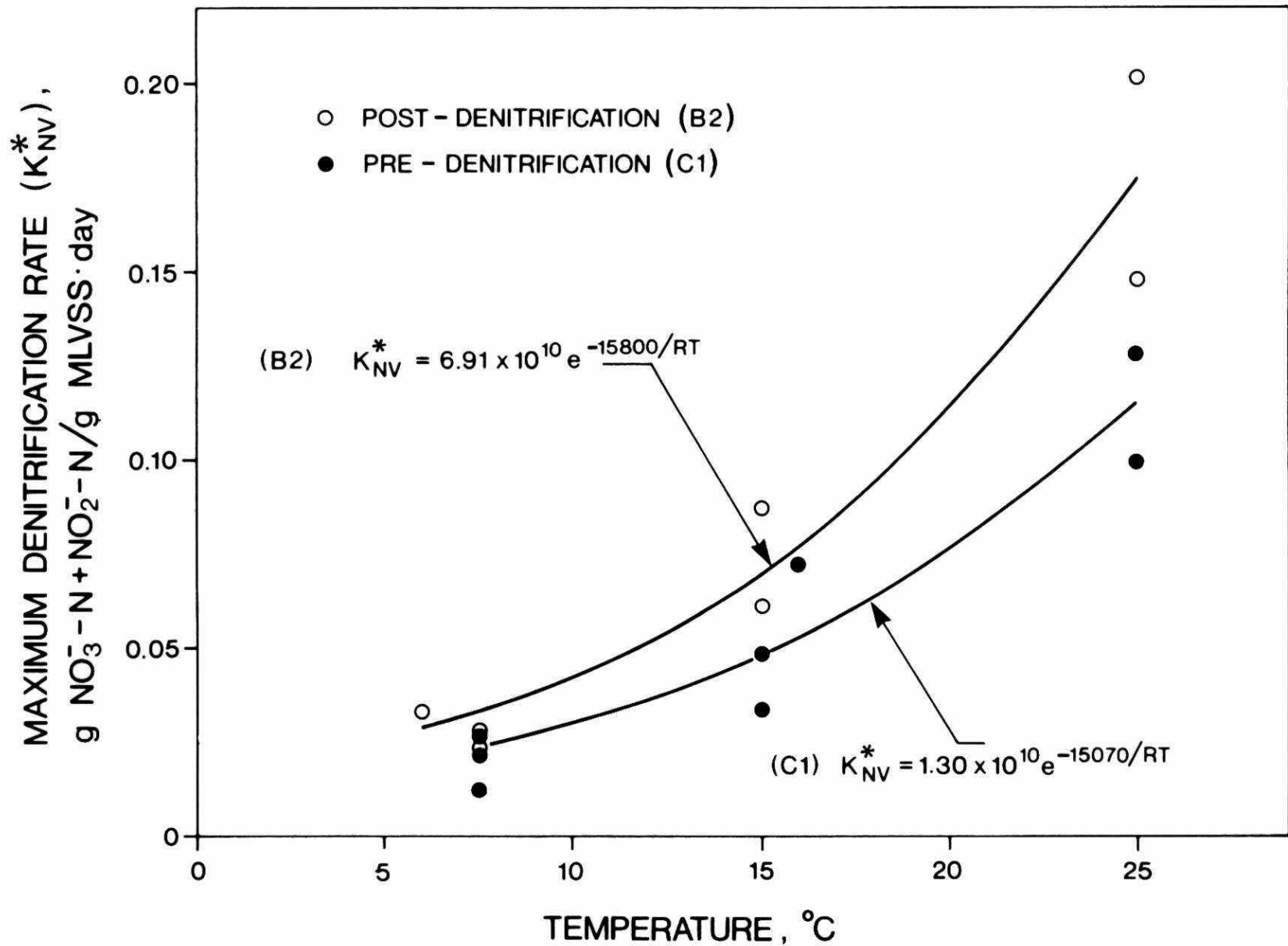


FIGURE 16. DENITRIFICATION RATES IN ANOXIC REACTORS B2 AND C1

TABLE 6. RELATIONSHIPS FOR DENITRIFICATION IN ANOXIC REACTORS B2 AND C1

Anoxic Reactor	$K_{NV}^*$ Models	Analysis of Variance Results		
		$\frac{\text{Mean Square Lack of Fit}}{\text{Mean Square Pure Error}}$	F $\alpha = 0.95$	F $\alpha = 0.99$
Post-Denitrification (B2)	$6.91 \times 10^{10} e^{-15800/RT}$	0.13	9.55	30.82
Pre-Denitrification (C1)	$1.30 \times 10^{10} e^{-15070/RT}$	1.41	6.94	18.00
Post and Pre-Denitrification	$6.40 \times 10^{10} e^{-15880/RT}$	6.61	3.87	7.19

Although individual models were developed to describe the batch results from reactors B2 and C1, an analysis of variance indicated that a single Arrhenius model may be appropriate to describe the results (Table 6). A statistical procedure was used to compare the observed nitrate plus nitrite results from the denitrification reactors (B2 and C1) under continuous operation to the results predicted from the single Arrhenius model developed from the batch results. The procedure (Snedecor and Cochran, 1967) involved determining the mean difference ( $\bar{D}$ ) between the observed and predicted values and assessing its statistical significance (Table 7). The resulting 't' statistic was not significant for either the post or pre-denitrification reactors (Table 7) indicating the Arrhenius model developed from batch data may describe the results during continuous operation.

TABLE 7. DIFFERENCE IN THE OBSERVED AND PREDICTED NITRATE PLUS NITRITE-N RESULTS FROM POST AND PRE-DENITRIFICATION REACTORS

Reactor	$\bar{D}$	$S_D^2/n$	t	$t_{\alpha = 0.95}$
B2	-0.53	0.08	1.90	2.05
C1	0.09	0.01	0.94	2.03

Note:  $\frac{S_D^2}{n}$  = estimated variance of  $\bar{D}$ , where  
 $S_D^2 = \frac{\sum (D_i - \bar{D})^2}{n-1}$ ,  
 $D_i$  = observed - predicted effluent  $\text{NO}_3^- \text{-N} + \text{NO}_2^- \text{-N}$  results from denitrification reactor,  
 $\bar{D}$  = mean difference,  
 $n$  = number of paired data points, and  
 $t = \frac{\bar{D}}{S_D / (n)^{1/2}}$ .

The denitrification rates found in this study were compared to results found by other authors in single sludge systems in which denitrification was proceeding under non-carbon limiting conditions (Figure 17).

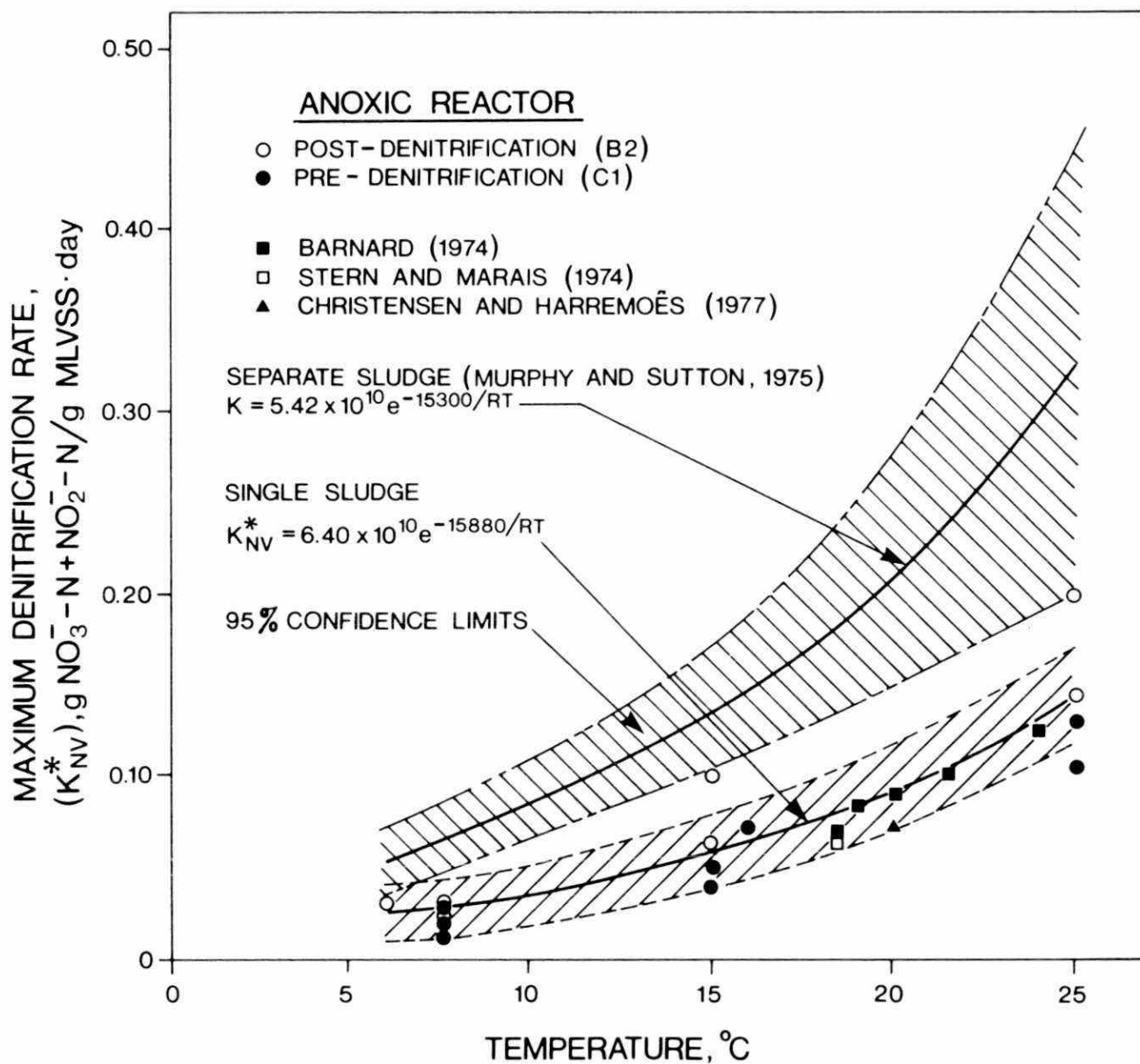


FIGURE 17. DENITRIFICATION RATES UNDER NON-CARBON LIMITING CONDITIONS

They were also compared to results obtained in a separate sludge denitrification system receiving an external carbon source (Figure 17). The rates, based on total volatile suspended solids, are significantly greater in the separate sludge system, although no difference in the temperature sensitivity of denitrification is evident (Figure 17). The larger rates may be expected as the fraction of active denitrifiers will be greater in the separate sludge system (equation 30) where the production of other organisms through aerobic carbon oxidation and nitrification will not occur. The single sludge denitrification results reported by other authors were from studies in which denitrification relied on excess organic carbon present in the influent sewage. The agreement between the results here and those results (Figure 17) indicate that the organics present in the raw sewage are comparable to methanol as an organic carbon source for denitrification. Parallel batch studies using sludge derived from the anoxic reactor of the pre-denitrification nitrification system verify these results (Figure 18). Details of the batch studies are contained in Appendix B (Table B6). Researchers at the Stevenage laboratory in England recently observed higher denitrification rates with sewage than with methanol under non-carbon limiting conditions (Paskins et al, 1977). Barnard and Meiring (1977), in presenting design information for the pre-denitrification reactor of the Bardenpho system, claim that the denitrification rate using sewage as the carbon source will be comparable to that observed using methanol. Although high rates of denitrification have been observed using sewage, it must be remembered that wastewaters may vary in the relative distribution of easily degraded and hard to degrade compounds causing variations in the denitrification rates between locations (U.S. EPA, 1975).

An alternative approach to using  $K_{NV}^*$  in the design of denitrification reactors in which nitrate reduction is proceeding at its maximum rate, is to specify the minimum anoxic SRT. The minimum anoxic SRT in reactors B2 and C1, at which complete denitrification was obtained, was 0.5 to 1.5 days at 24° to 26°C, 1.0 to 2.0 days at 14° to 16°C and 4.0 to 5.0 days at 7° to 8°C.

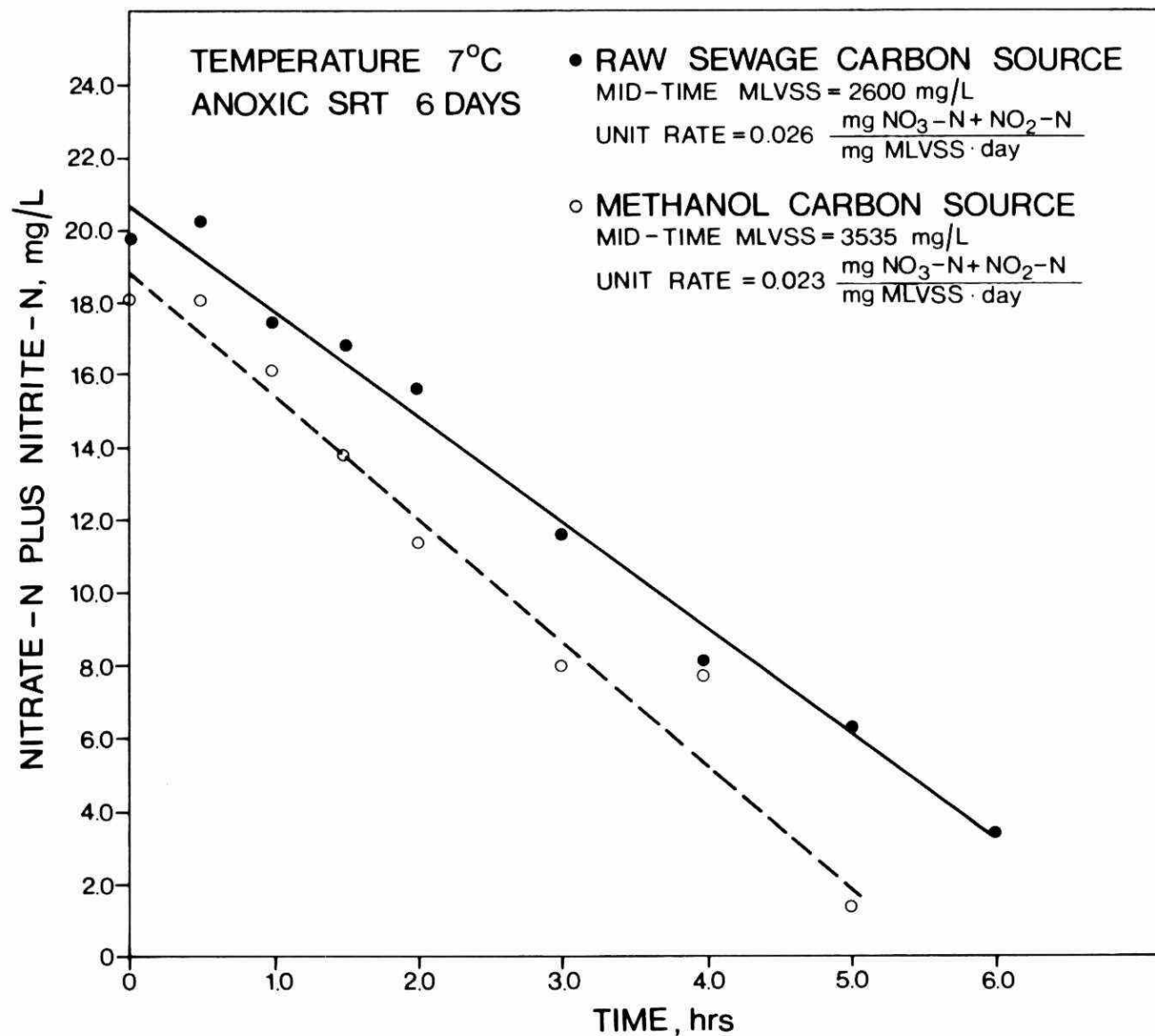


FIGURE 18. DENITRIFICATION RATES WITH METHANOL AND RAW SEWAGE AS CARBON SOURCES

#### 4.2.2 Organic carbon requirements for maximum denitrification rates

Once the quantity of organic carbon required for bacterial growth and reduction of nitrate, nitrite and dissolved oxygen fed to the anoxic reactor becomes limiting, denitrification will no longer proceed at the maximum rate. Following completion of the continuous runs, according to the initial experimental design (Table 2), the quantity of organic carbon necessary to avoid limitation of denitrification was determined by varying the feed rate of methanol to the pre and post-denitrification reactors (Figure 1, reactors B2 and C1) and operating the pre-denitrification system with no methanol addition (Figure 1, system D).

The results from the post-denitrification system (Figure 1, system B), indicate that the effluent  $\text{NO}_3^-$ -N concentration at which the denitrification reaction will become carbon limited can be determined from equation 24 (Figure 19). The filterable COD available to the anoxic reactor is that added as methanol. The equivalent  $\text{NO}_3^-$ -N reduced was determined by comparing the anoxic reactor influent and effluent values for  $\text{NO}_3^-$ -N,  $\text{NO}_2^-$ -N and  $\text{O}_2$ , and expressing the results in terms of  $\text{NO}_3^-$ -N equivalents.

The results from the pre-denitrification systems (C and D) indicate that unless a minimum of approximately eight grams of filterable COD are available for each gram of equivalent  $\text{NO}_3^-$ -N reduced, the extent of denitrification will be limited (Figure 19). The filterable COD available for denitrification in this system was determined by comparing the anoxic reactor influent filterable COD, including that due to methanol addition, to the effluent value from the aerobic reactor (Figure 1, reactors C2 and D2). If the filterable COD available was entirely in the form of methanol, the stoichiometric COD requirement, including that necessary for assimilation, would be 3.7 times the equivalent  $\text{NO}_3^-$ -N reduced according to equation 24. Barnard (1973) found the ratio of the COD required to equivalent  $\text{NO}_3^-$ -N reduced was 10.0 in a pre-denitrification reactor. Stern and Marais (1974) and Marsden and Marais (1976), operating bench scale pre-denitrification nitrification systems, found the ratio to be greater than 15. They concluded that the reason for the excessive COD requirement in a pre-denitrification reactor is a rapid initial removal of COD by adsorption.

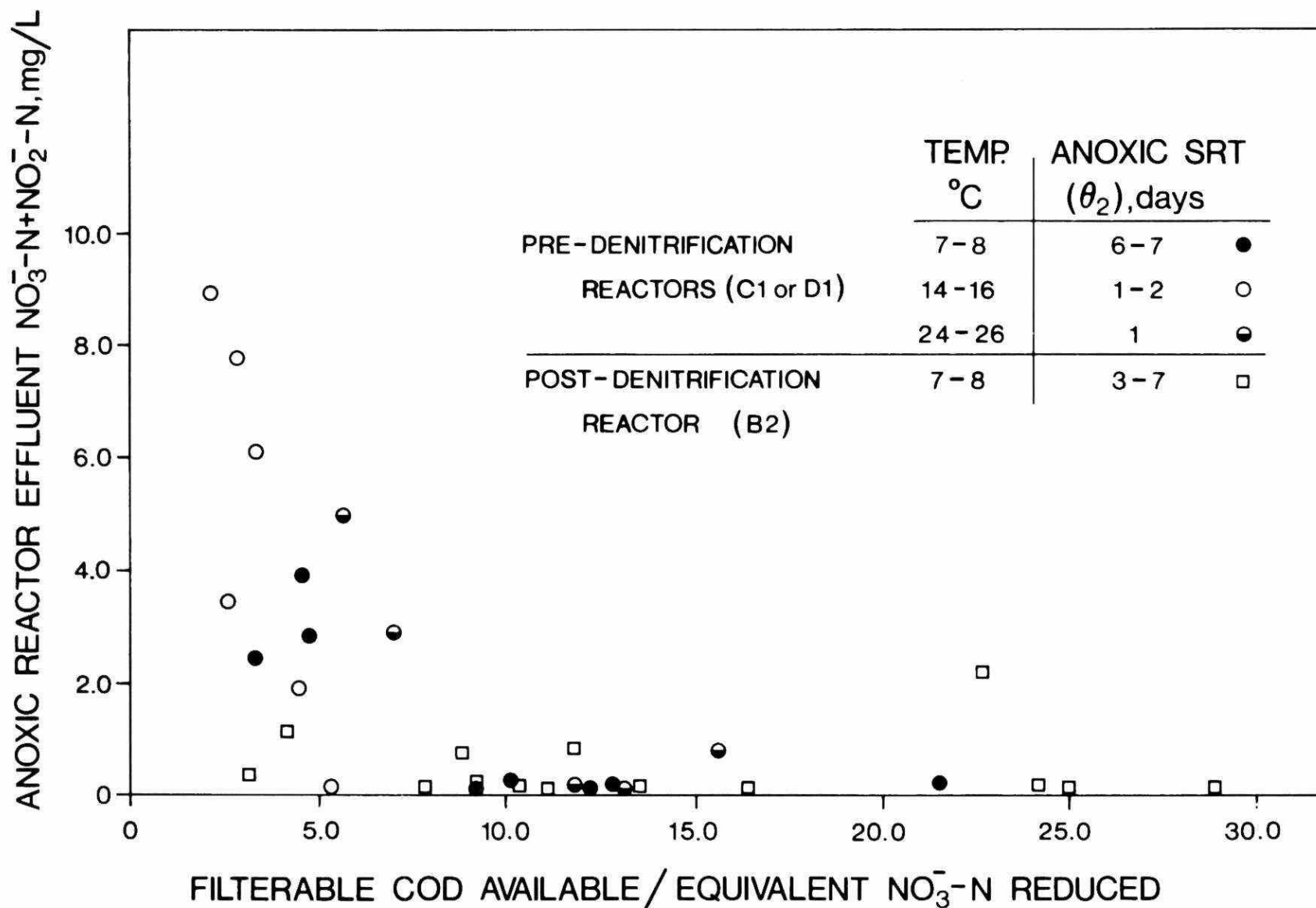


FIGURE 19. ORGANIC CARBON REQUIREMENTS IN POST AND PRE-DENITRIFICATION REACTORS



The organic carbon requirements for complete denitrification in reactor C1 can also be expressed in terms of the value of influent C to N ratio at which nitrate appeared in the anoxic reactor. In this study, unless a minimum of 13 to 15 grams of unfiltered COD per gram of unfiltered TKN was fed to the system, denitrification was not complete (Figure 20). Only results where complete nitrification was obtained (ammonia-N less than or equal to two) are included in Figure 20. Details of the calculations necessary for preparation of Figures 19 and 20 appear in Appendix B.

Pilot plant studies by Osborn and Nicholls (1977) indicated a carbon limitation on nitrate removal in a pre-denitrification nitrification system at an influent COD to  $\text{NH}_3\text{-N}$  ratio of approximately 20. They felt that the scale of their pilot plant reactors affected the result and that an influent COD to nitrogen ratio of 11.5, as proposed by Barnard and Meiring (1977), was sufficient to ensure complete nitrate removal in the pre-denitrification reactor. The pilot plant reactors operated by Osborn and Nicholls (1977) were approximately one-tenth of the size of the reactors employed in this study.

#### 4.2.3 Effect of reactor configuration on denitrification

From the information on organic carbon requirements (Figure 19) and from the maximum denitrification rate results (Figure 17), it can be concluded that the location of the anoxic reactor in the post or pre-denitrification configuration has no influence on the nitrate removal rate under non-carbon limiting conditions. The independence of reactor configuration and denitrification rate was further verified from operation of the step-feed nitrification-denitrification system (Figure 1, system E). Comparable results were obtained in this system and in the pre-denitrification systems (Figure 1, systems C and D). The effect of the C:N ratio on the systems under identical temperature and SRT conditions, is illustrated in Figure 21. In this figure, the effect of the C:N ratio is expressed by plotting the final effluent oxidized nitrogen concentration. Only results where complete nitrification was obtained are included (Appendix B, Table B9). Data from two experimental runs carried out according to the initial experimental design of Phase 1 (Table 2) were included to supplement the information.

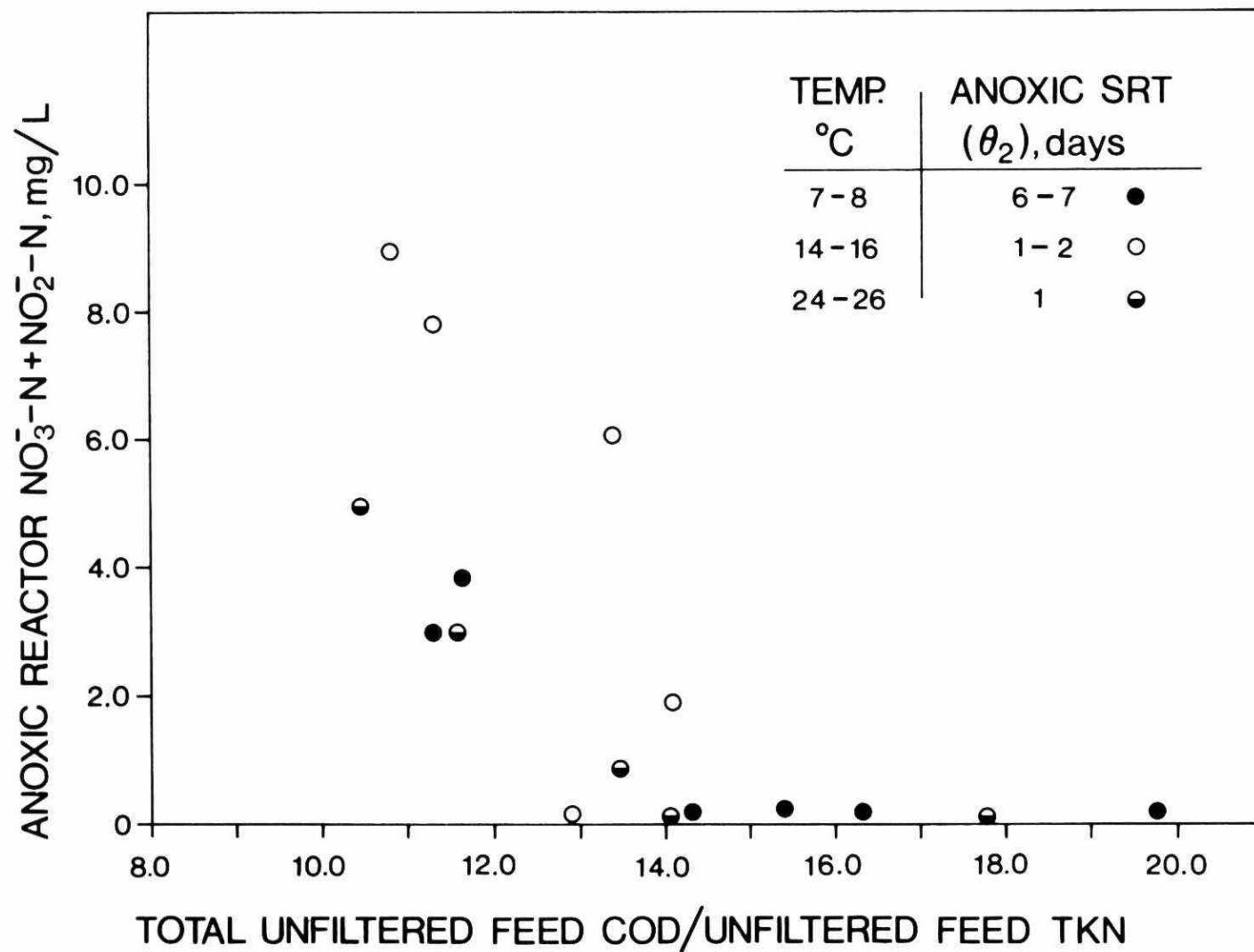


FIGURE 20. INFLUENT C:N RATIO EFFECT ON NITRATE REDUCTION IN PRE-DENITRIFICATION REACTOR

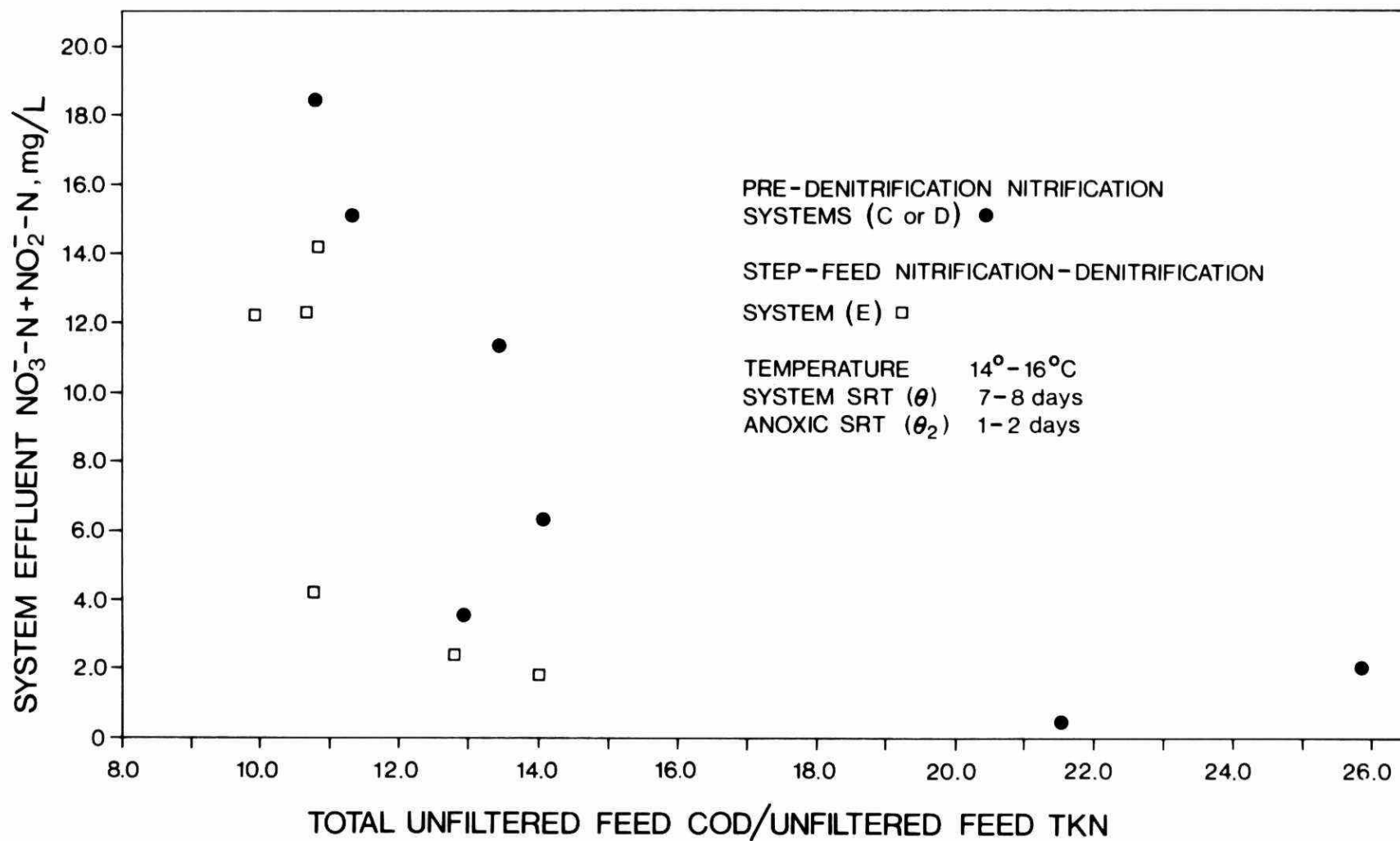


FIGURE 21. INFLUENT C:N RATIO EFFECT ON NITRATE REDUCTION IN STEP-FEED AND PRE-DENITRIFICATION SYSTEMS

#### 4.2.4 Denitrification results under carbon limiting conditions

High filtered N removals are possible only when complete denitrification occurs in the anoxic reactors of the single sludge systems. In many instances, the organics in the raw sewage will not be present in sufficient quantity to provide complete denitrification in the anoxic reactors (Figure 19). Parallel batch reactor studies (Appendix B, Table B7), using sludge derived from the anoxic reactor of the pre-denitrification system, indicate that under these conditions complete nitrate removal can be obtained by relying on the endogenous respiration of the biological sludge to complete the reaction (Figure 22). In this case, the rate of nitrate reduction initially proceeds under non-carbon limiting conditions and then reduces to a rate equivalent to the endogenous rate (Figure 22). The reduced overall rate of nitrate reduction is equivalent to a reduction in the growth rate of the denitrifiers. Consequently, to obtain complete nitrate reduction under these conditions, the SRT in the anoxic reactor of the pre-denitrification nitrification system must be increased. Comparing the non-carbon limited and endogenous nitrate removal rates (Figure 22), if the anoxic SRT was increased by a factor of 2.5, the resulting SRT should be more than sufficient to obtain complete denitrification.

This is verified by continuous results from the pre-denitrification nitrification system under carbon limiting conditions (Figure 23). Only results where complete nitrification was obtained are included in Figure 23. Complete denitrification was obtained under the increased anoxic SRT conditions at an influent unfiltered COD to TKN ratio as low as nine. Similar findings have recently been reported by Van Vuuren and Wiechers (1977). They operated a 130 m<sup>3</sup> per day pre-denitrification nitrification pilot plant in South Africa. The feed to the plant was primary lime treated municipal sewage with a COD to NH<sub>3</sub>-N ratio of approximately five. From their data, recorded during operation at the same recycle ratios as employed in this study, it can be shown that at an initial anoxic SRT of four days, denitrification was not complete in the anoxic reactor. When the anoxic HRT was increased by a factor of 1.8, thereby increasing the SRT, complete denitrification was obtained. Unfortunately, the temperature during these studies was not stated.

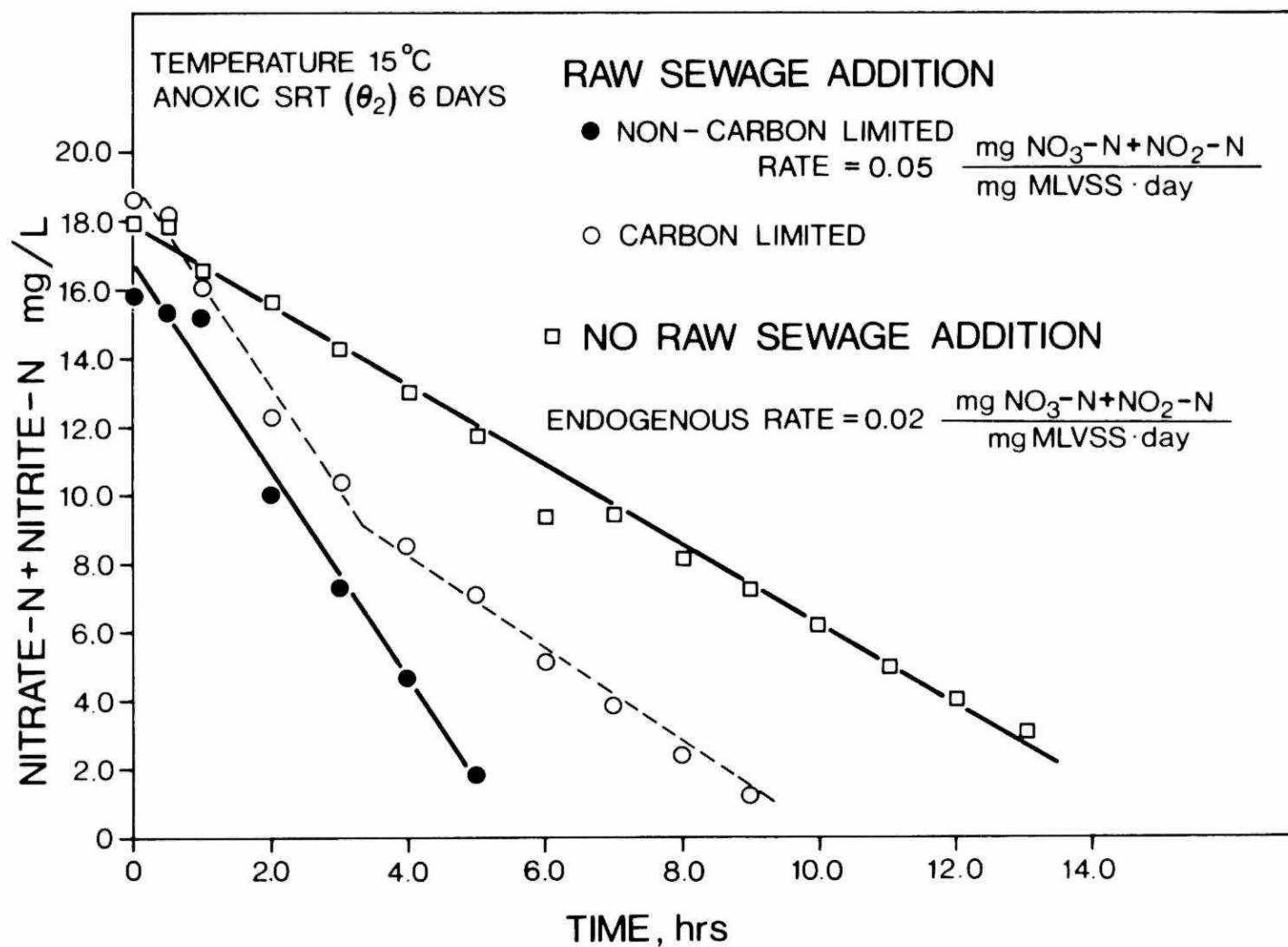


FIGURE 22. BATCH DENITRIFICATION RESULTS UNDER CARBON AND NON-CARBON LIMITING CONDITIONS

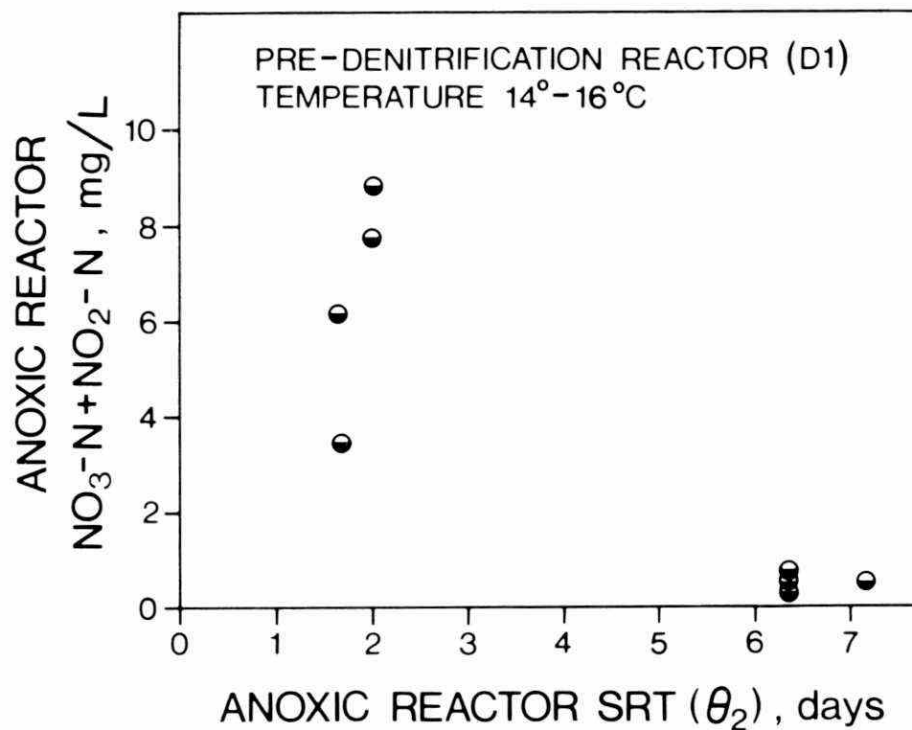


FIGURE 23. ANOXIC REACTOR SRT REQUIREMENTS  
IN THE PRE-DENITRIFICATION SYSTEM  
UNDER CARBON LIMITING CONDITIONS

Denitrification rates under non-carbon limiting conditions (Figure 17) and under conditions where the endogenous respiration of the biological sludge controls the rate of denitrification represent, respectively, the maximum and minimum values attainable in the anoxic reactor(s) of the single sludge systems. The choice of the rate, for design purposes, and the corresponding SRT required for the anoxic reactor, will be determined from knowledge of the organic carbon requirements (Figures 19 to 21), and the influent C to N ratio.

Continuous and batch experiments within the anoxic reactor of system A allowed determination of the rates where endogenous respiration of the biological sludge provided the carbon and energy source. The wide variation in the rates observed (Figure 24) and those reported by other authors may be due to the dependence on the system SRT. The observed rates decreased with increasing SRT in this study (Figure 25) and in studies by Stern and Marais (1974) and Beer et al (1977). If the

reason for this relates to the decrease in the number of viable organisms at longer SRT's, as proposed previously, the rate variation should be reduced if the rates are expressed in terms of the active total volatile suspended solids by using equation 12. The results (Figure 26) indicate that this equation alone cannot explain the dependence of the denitrification rate on system SRT. It should be noted that the effects of temperature and SRT interact and may be confounded in Figures 25 and 26.

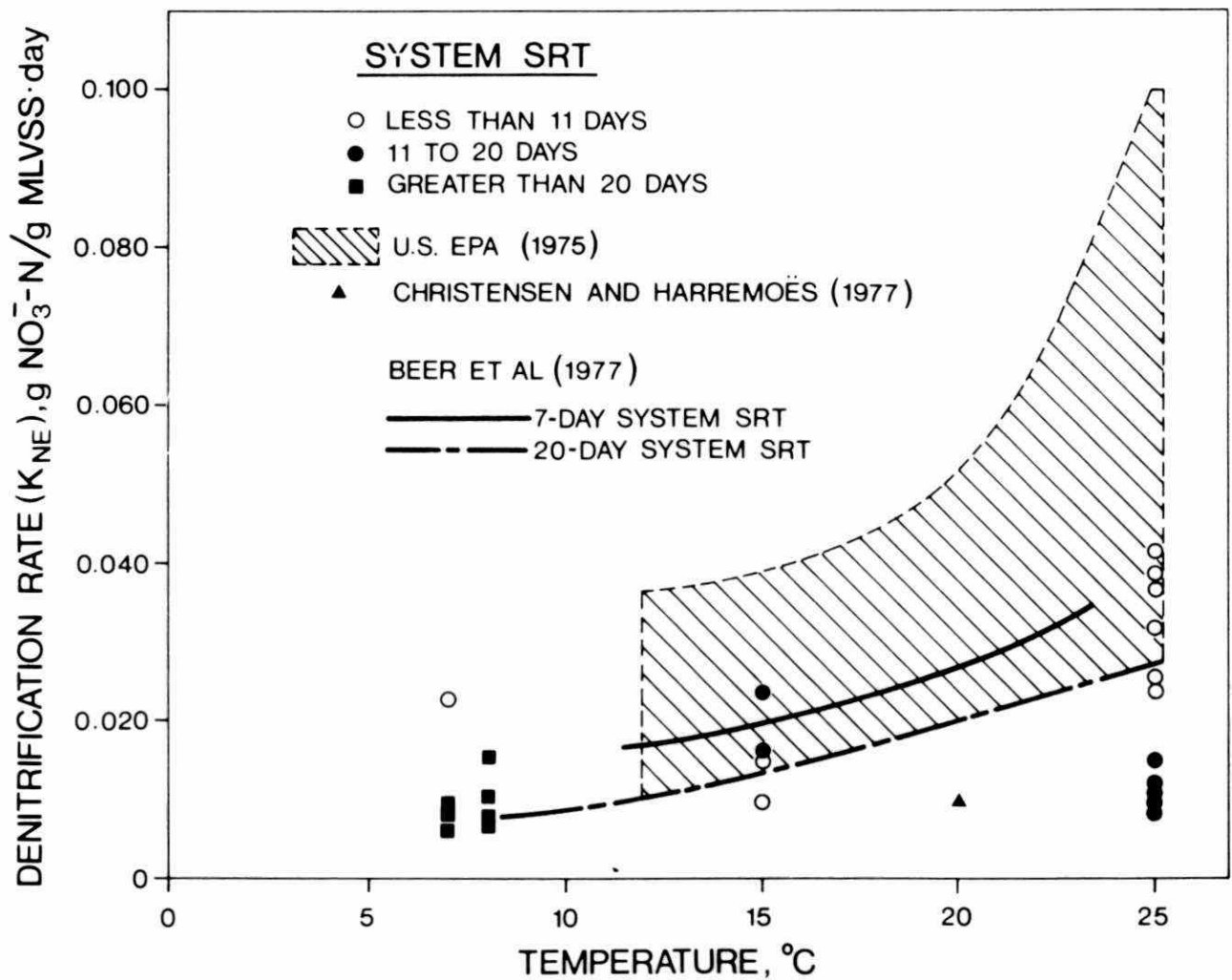


FIGURE 24. DENITRIFICATION RATES USING ENDOGENOUS CARBON SOURCES

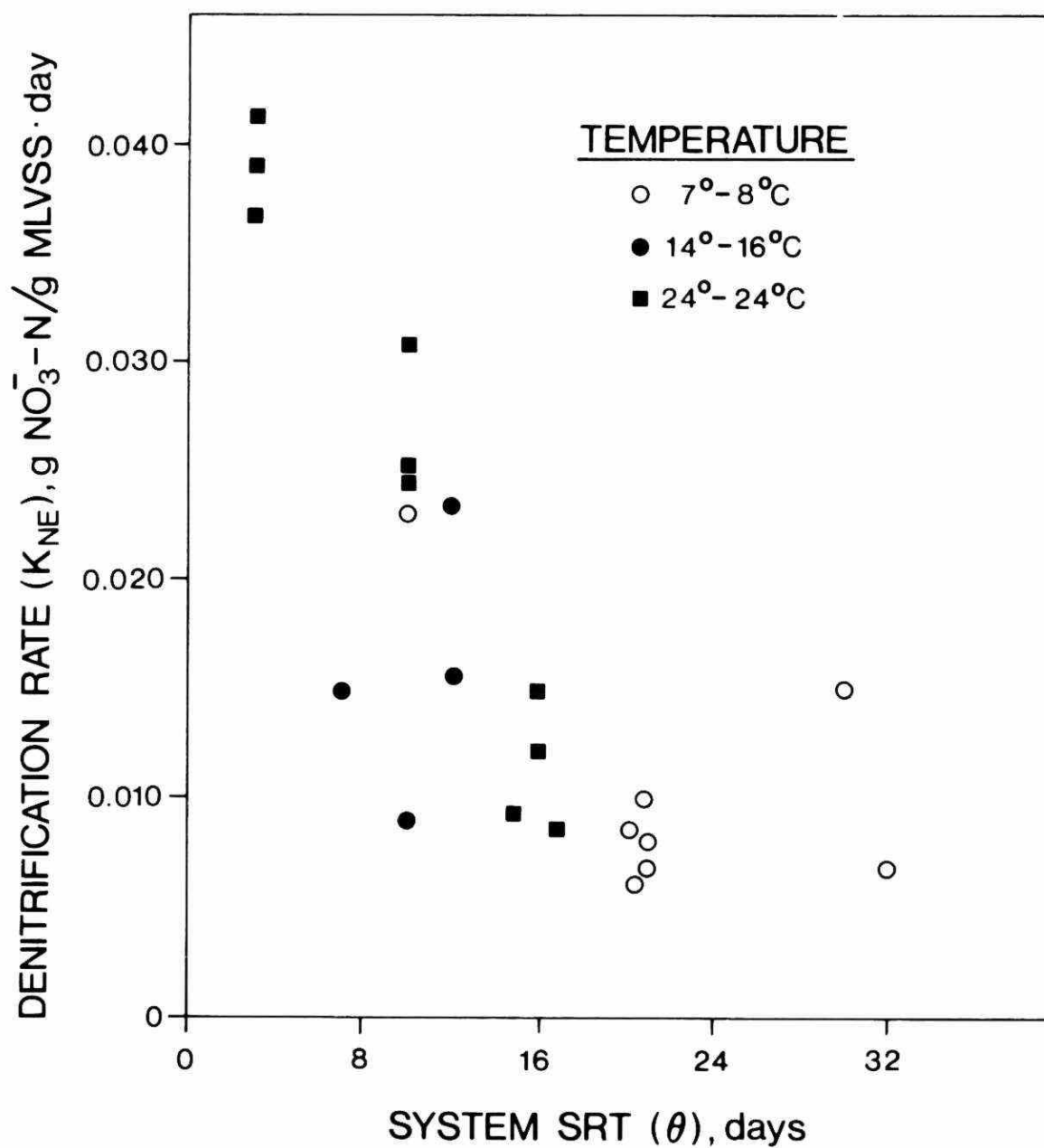


FIGURE 25. EFFECT OF SOLIDS RETENTION TIME ON ENDOGENOUS DENITRIFICATION RATES



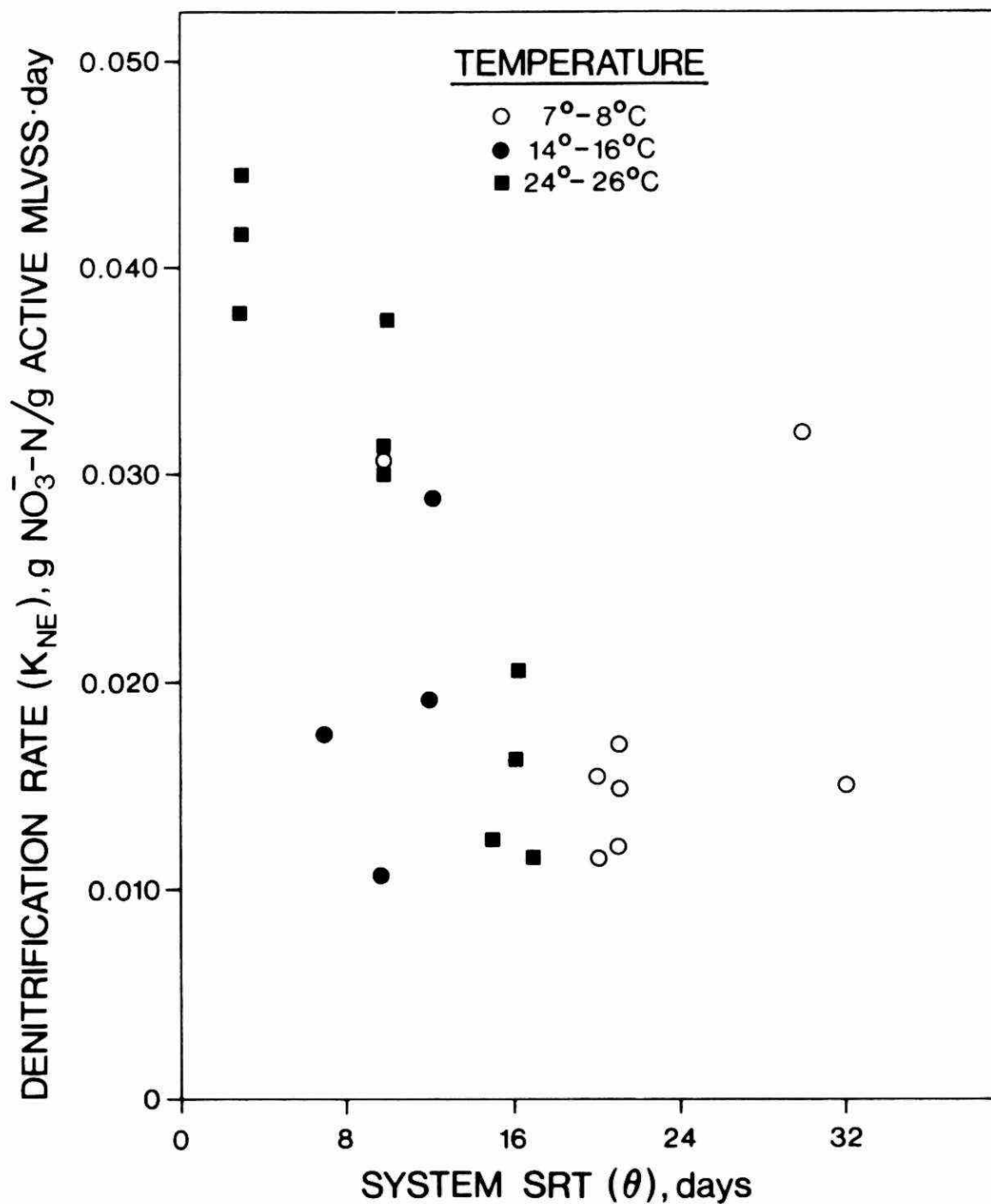


FIGURE 26. EFFECT OF SOLIDS RETENTION TIME ON ENDOGENOUS DENITRIFICATION RATES BASED ON ACTIVE VOLATILE SUSPENDED SOLIDS

The effect of the system SRT on denitrification, when controlled by endogenous respiration, complicates the determination of the temperature sensitivity of the process. If the rate of denitrification is controlled by the endogenous respiration rate, the temperature sensitivity of the processes should be equal. According to Eckenfelder (1975), the endogenous respiration rate increases only 1.4 times for each 10°C change in temperature between 10° and 30°C. Grouping the results in this study according to the system SRT, little or no temperature effect on the denitrification rate is evident (Figure 24). This result supports the theory of Stern and Marais (1974), but is in contrast to the results of Barnard (1974) who reported a much larger temperature sensitivity for denitrification relying on endogenous respiration. The results (Figure 24) reported by Beer et al (1977), using sludges from secondary treatment plants, were not derived under equilibrium temperature conditions.

#### 4.3 System Performance and Design Considerations

##### 4.3.1 Sludge production

An important parameter required for the design of any activated sludge system is the solids yield coefficient. In a single sludge carbon oxidation, nitrification and denitrification system, it is not possible to determine the yield coefficient associated with each biological process. In this study, a system yield coefficient was determined from the relationship:

$$\frac{1}{\theta} = YK - b \quad (35)$$

where:  $K = \frac{Q(S_o - S)}{X_M V}$

$Q$  = volumetric flow rate ( $L \cdot \text{day}^{-1}$ )

$S_o$  = influent total COD ( $\text{mg} \cdot L^{-1}$ )

$S$  = effluent filterable COD ( $\text{mg} \cdot L^{-1}$ )

$X_M$  = mixed liquor volatile suspended solids concentration ( $\text{mg} \cdot L^{-1}$ )

$V$  = biological reactor volume (L)

$b$  = organism decay coefficient ( $\text{day}^{-1}$ )

$= 0.10 (1.03)^{T-20}$  (Eckenfelder, 1975)

T = temperature ( $^{\circ}\text{C}$ )

Y = organism system yield coefficient ( $\text{mg}\cdot\text{mg}^{-1}$ )

$\theta$  = system SRT (day)

The mean value of Y was found to be 0.57 mg of VSS per mg of COD removed (Figure 27). This value represents the yield coefficient for the single sludge systems in which no external carbon source was added to the anoxic reactor or in which an external carbon source (methanol) was added but only in sufficient quantities to prevent the organic carbon content limiting the denitrification rate. In computing Y, the experimental results for systems B and C, conducted according to the initial experimental design in Phase I (Table 2), were not used.

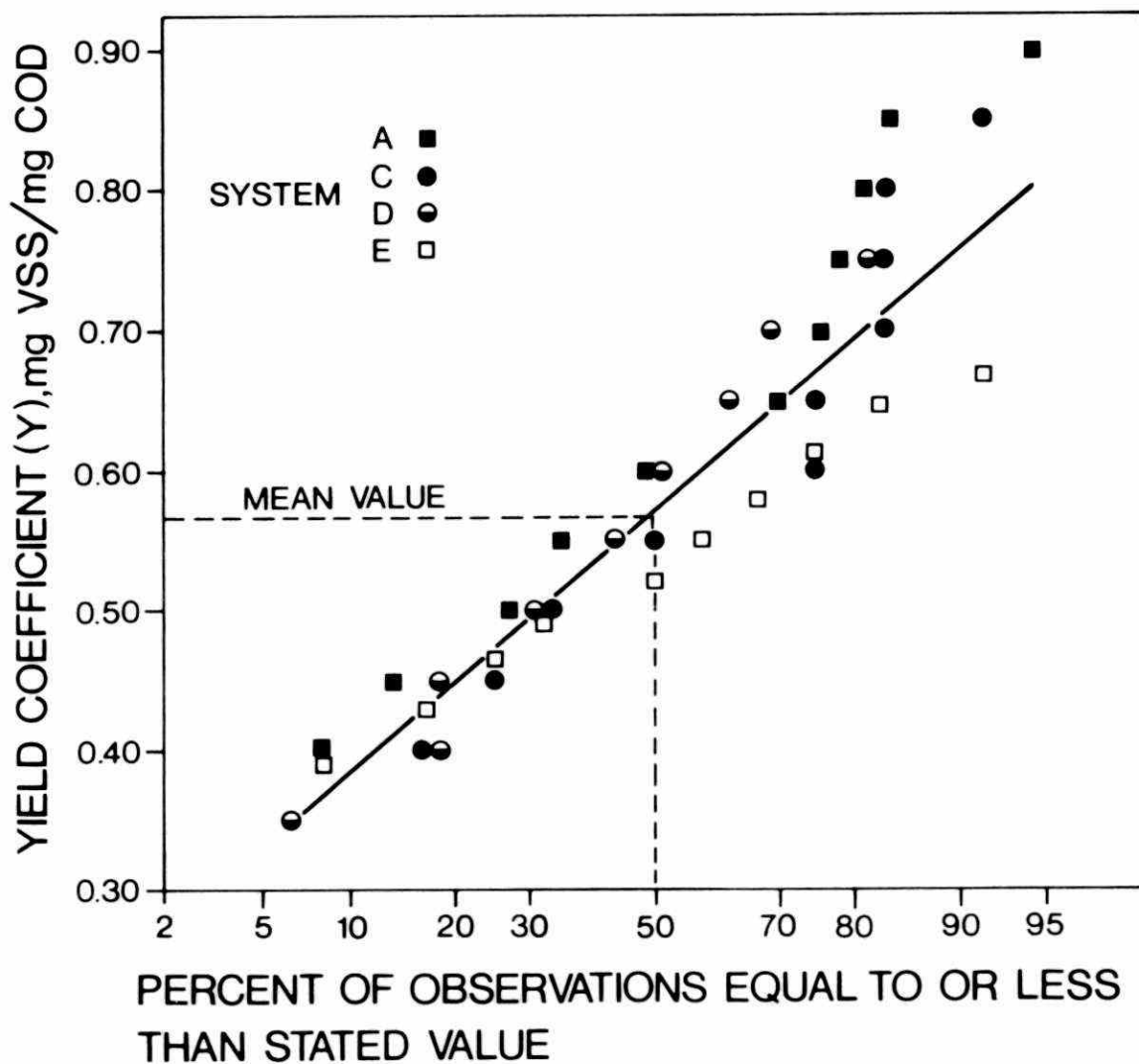


FIGURE 27. SLUDGE PRODUCTION IN SINGLE SLUDGE SYSTEMS

#### 4.3.2 Alkalinity consumption

The observed and theoretical alkalinity demands in the post and pre-denitrification systems were compared in this study to determine the validity of the stoichiometric equations for nitrification (equations 1, 2 and 3) and for denitrification (equations 18, 22 or 26). The theoretical alkalinity demand due to nitrification was based on the difference between the influent filterable TKN available for nitrification and the effluent value. The theoretical alkalinity formed due to denitrification was based on the difference between the nitrogen oxidized in the aerobic reactors and the final oxidized nitrogen concentration. The mean value for the ratio of the observed to the theoretical net alkalinity consumed was 0.8 for the post-denitrification systems and 1.5 for the pre-denitrification systems (Figure 28). The difference in ratios between the post-denitrification and pre-denitrification systems could not be explained.

#### 4.3.3 Phosphorus removal

Studies in South Africa (Barnard, 1975; Osborn and Nicholls, 1977) have indicated that if a pre-anaerobic zone is created in an activated sludge system, a high degree of phosphorus removal can be attained without chemical addition. In the pre-denitrification systems (C and D) studied here, when the  $\text{NO}_3^-$ -N plus  $\text{NO}_2^-$ -N concentration in the anoxic reactors goes to zero, anaerobic conditions will be created. The observed pilot plant results indicate enhanced filterable P removal under these conditions (Figure 29). The effluent filterable P results from the single sludge post-denitrification systems (Figure 1, systems A and B) compare to that from the pre-denitrification system when anaerobic conditions were not reached in the anoxic reactor (Figure 29).

#### 4.3.4 Effluent quality attainable

From the information presented, the aerobic and anoxic reactors of the single sludge systems can be designed to reduce respectively, the ammonia and oxidized nitrogen concentrations to less than 1 mg/L N. The wide variation in reported denitrification rates from the anoxic reactor

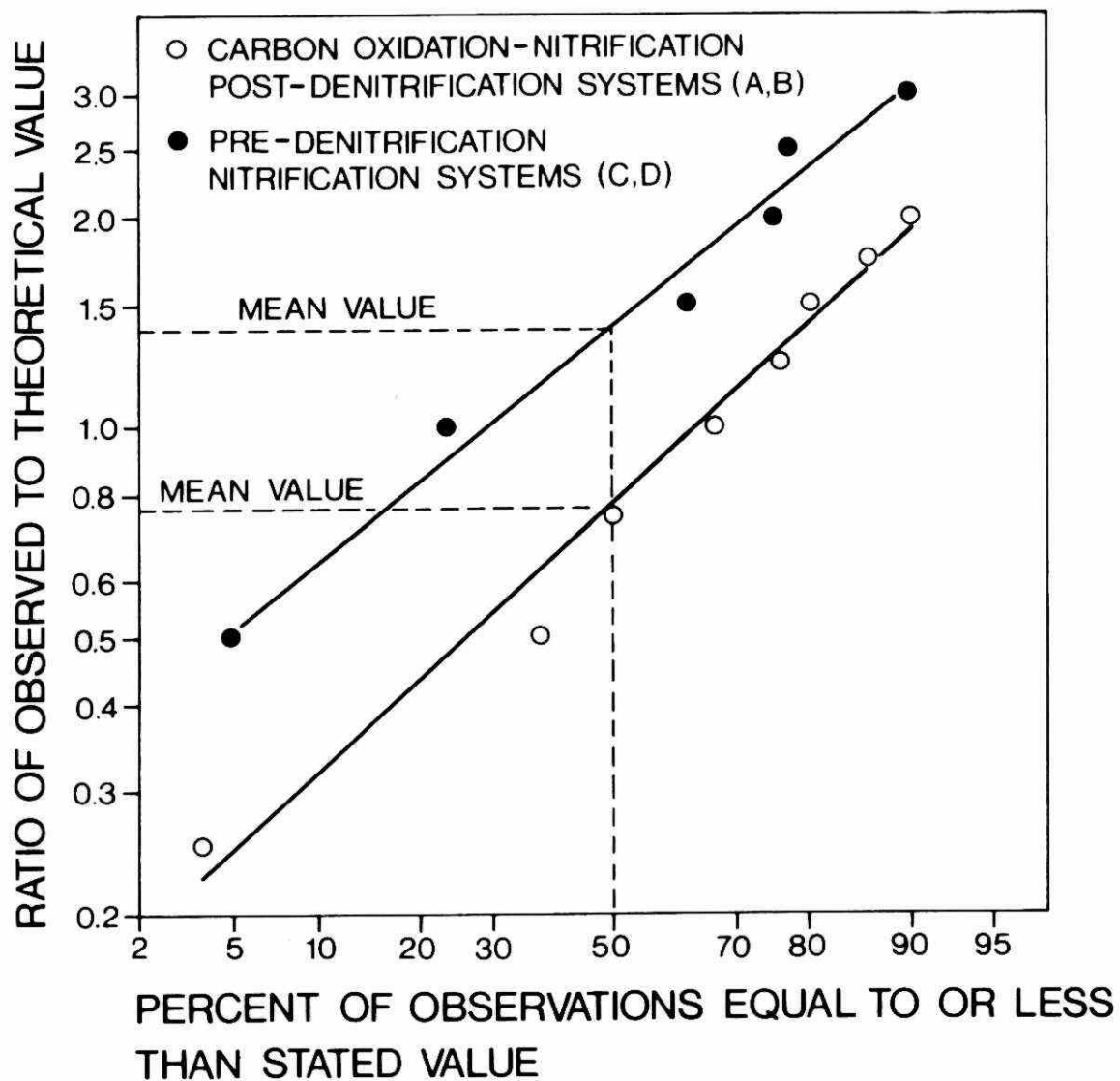


FIGURE 28. ALKALINITY CONSUMPTION IN SINGLE  
SLUDGE SYSTEMS

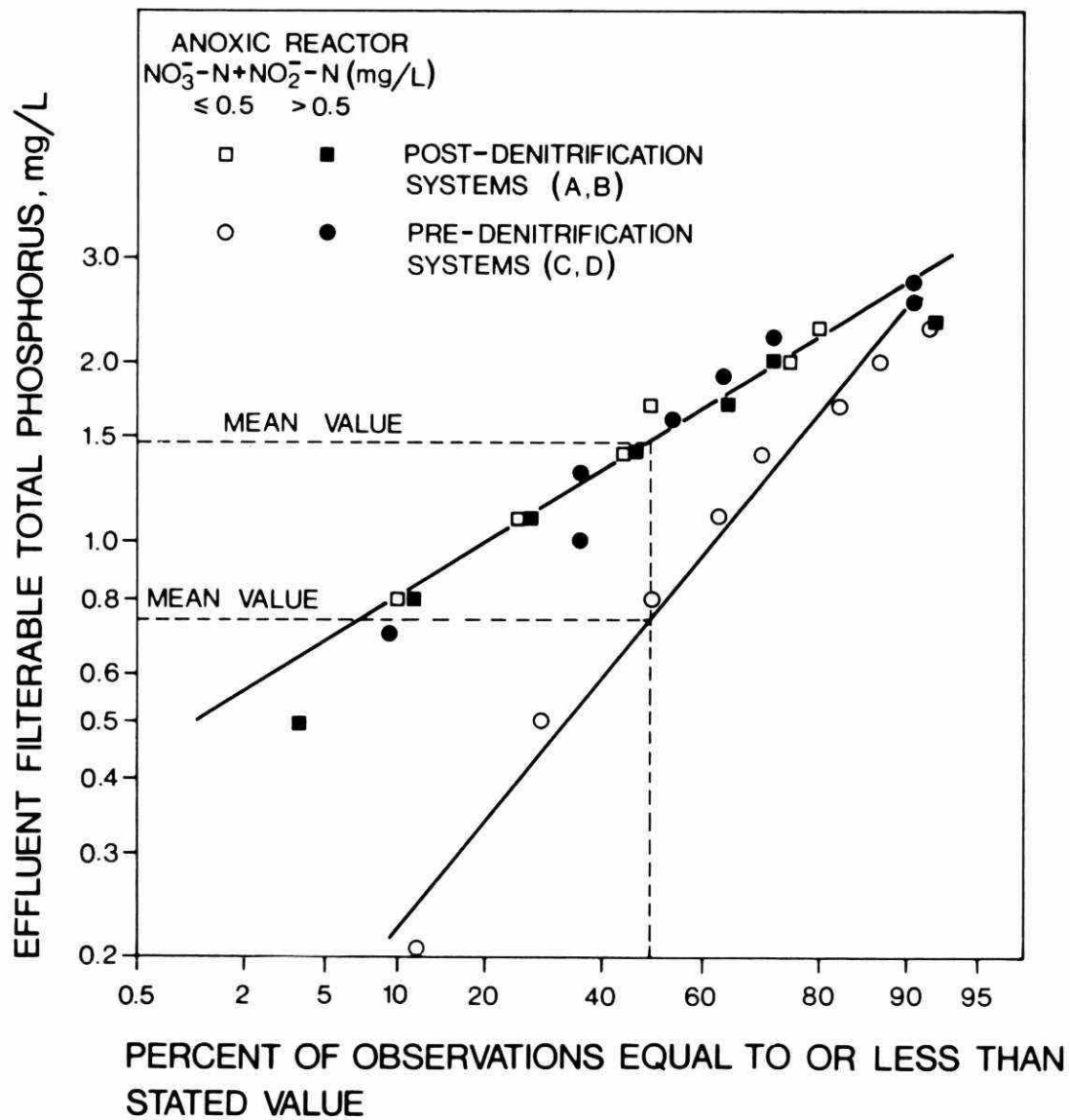


FIGURE 29. EFFLUENT P RESULTS FROM POST AND PRE-DENITRIFICATION SYSTEMS

in which endogenous respiration of the biological sludge controlled the rate of denitrification (Figure 24) indicates that consistently low effluent oxidized nitrogen concentrations may not be attainable from a system relying on this mode of denitrification.

Although essentially complete ammonia reduction can be achieved in the aerobic reactors, the maximum fraction of filterable TKN removal is limited by the residual filterable organic nitrogen (Figure 11). The nitrogen associated with the effluent suspended solids will increase the total nitrogen content of the effluent. In the single sludge systems studied here, the N in the effluent suspended solids was normally in the range 5% to 8%. If the concentration of suspended solids was 20 mg/L, an additional 1.0 to 1.6 mg/L of N will result. Even if complete ammonia removal and nitrate reduction was achieved in the post-denitrification systems (Figure 1, systems A and B), the minimum effluent nitrogen level attainable will be 2 to 3 mg/L of total N considering both the filterable (Figure 11) and non-filterable fractions.

In the post-denitrification system, relying on endogenous respiration to supply the carbon source for denitrification (Figure 1, system A), the release of ammonia (equation 18) may increase the effluent N concentration. The results from the batch experiments in the anoxic reactor of system A (Appendix B, Table B5) and the paired data comparison of the effluent filterable TKN from the aerobic and anoxic reactors (Figure 7), indicate that the ammonia release is negligible. This is not surprising as according to the stoichiometric equation (18) only 0.25 mg of  $\text{NH}_3\text{-N}$  will be released per mg of nitrate or nitrite reduced.

In the pre-denitrification nitrification systems (Figure 1, systems C and D), even though complete nitrate removal and ammonia oxidation is obtained in the anoxic and aerobic reactors, respectively, the process configuration limits the filterable nitrogen removal (Figure 4). The significance of obtaining complete nitrate removal in the anoxic reactor is illustrated in Figure 30 at the recycle ratios employed in this study. The observed total filtered N removal results in the pre-denitrification nitrification systems were compared to the theoretical values. Only results in which the anoxic reactor effluent nitrate-nitrogen plus nitrite-nitrogen was less than or equal to 0.2 mg/L were

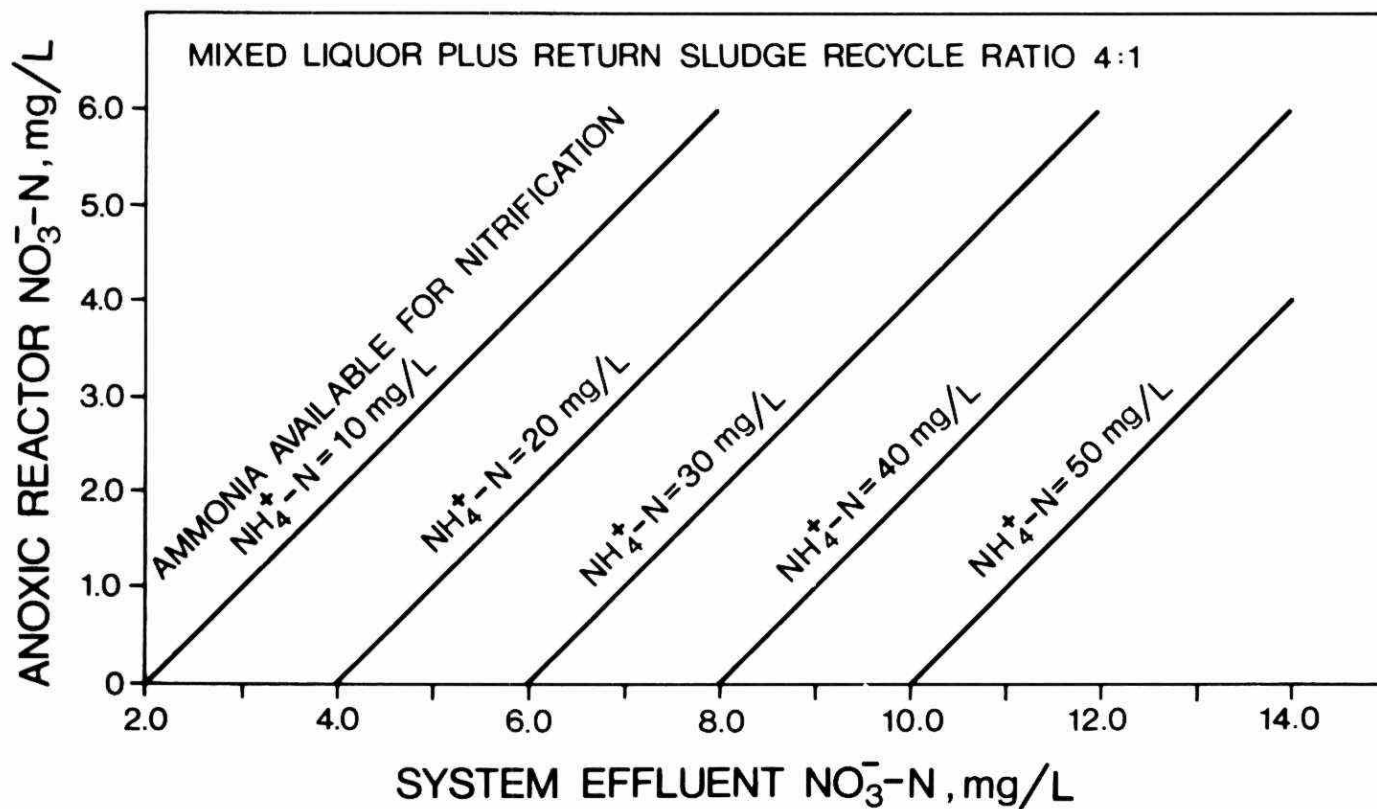


FIGURE 30. THEORETICAL MINIMUM EFFLUENT NITRATE CONCENTRATION FROM PRE-DENITRIFICATION NITRIFICATION SYSTEM



considered. By calculating the nitrogen assimilated and adjusting the theoretical results accordingly, good agreement was found between observed and theoretical results (Figure 31). In this study, the total filterable nitrogen removal was approximately 90% of the filtered TKN removal when complete denitrification was obtained in the anoxic reactor.

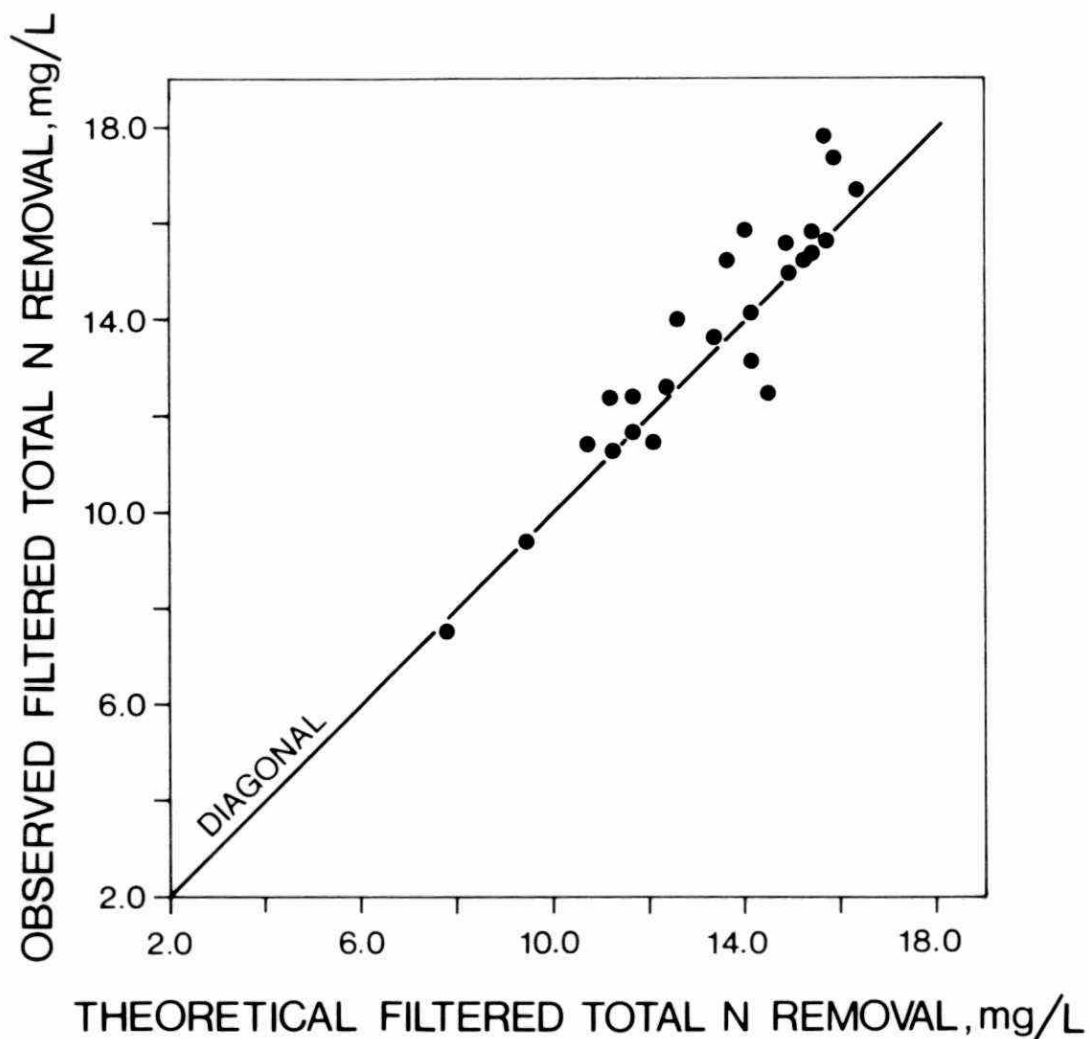


FIGURE 31. OBSERVED AND THEORETICAL N REMOVAL IN PRE-DENITRIFICATION NITRIFICATION SYSTEMS

The observed percent filterable N removal in the step-feed system was approximately 90% when complete nitrate and ammonia removal was obtained in the anoxic and aerobic reactors, respectively. From a mass balance around the biological reactors, it can be shown (equation 34) that, in this study, at the feed ratio to the final denitrification stage and return sludge recycle ratio employed, the theoretical filtered nitrogen removal is 90% of the influent N available for nitrification.

## 5.1

Nitrification in Single Sludge Systems

1. The degree of nitrification in single sludge systems, whether expressed as the fraction of ammonia or filterable TKN removal, will be dependent on the aerobic SRT.
2. The maximum filterable TKN removal, 90% to 95% will be limited by a residual filterable organic nitrogen in the effluent. The mean value of the residual filterable organic nitrogen can be estimated at 1.2 mg/L.
3. Under variable influent conditions, the capacity for filterable TKN or ammonia removal will increase as the operating aerobic SRT increases beyond the minimum necessary for nitrification.
4. Periods of up to 4.0 hr of anoxic conditions will have no effect on nitrifying organisms.
5. The growth rate and temperature sensitivity of nitrifiers in aerobic-anoxic single sludge systems and in purely aerobic systems will be comparable.

## 5.2

Denitrification in Single Sludge Systems

1. Under non-carbon limiting conditions, the denitrification rates, expressed as mg of oxidized nitrogen removed per mg of MLVSS per day, in separate sludge systems will be significantly higher than in single sludge systems. The temperature sensitivity of the rate of denitrification under these conditions will be no different in separate or single sludge systems.
2. The organics present in the influent sewage fed to the single sludge systems in this study were comparable to methanol as an organic carbon and energy source for denitrification.

3. In separate and single sludge post-denitrification systems, the methanol required to ensure that denitrification proceeds under non-carbon limiting conditions will be similar. In single sludge pre-denitrification and step-feed denitrification systems, the methanol requirements will be more than double that required in separate sludge systems.
4. Under carbon limiting conditions, complete denitrification can be achieved in an anoxic reactor by relying on endogenous denitrification to complete nitrate removal.
5. The endogenous denitrification rates, expressed as mg of  $\text{NO}_3^-$ -N removed per mg of MLVSS per day, will be dependent on the system SRT. The denitrification rates will decrease with increasing SRT.
6. Little or no temperature sensitivity may be expected for denitrification proceeding under carbon limiting conditions.

### 5.3 Single Sludge System Performance

1. The mean value of the yield coefficient for single sludge systems, in which no external carbon source is added or in which methanol is added but only in sufficient quantities to prevent an organic carbon limitation on the denitrification rate, can be expected to be 0.57 mg VSS per mg COD removed.
2. The mean value for the ratio of the observed to theoretical alkalinity consumption in single sludge systems will vary between 0.8 for the post-denitrification systems and 1.5 for the pre-denitrification systems.
3. In a single sludge pre-denitrification nitrification system enhanced P removal may be expected when anaerobic conditions are achieved in the anoxic reactor.

4. The minimum effluent nitrogen level attainable in single sludge nitrogen removal systems will be 2 to 3 mg/L of total N. Depending on the single sludge process configuration, these effluent values may not be attainable.

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## APPENDIX A

Solids Retention Time (SRT) Calculations

Analytical Procedures

Relationships for Filterable TKN Assimilated

Determination of Aerobic SRT Required for  
Nitrification

Computer Program for Parameter Determination  
for Linear and Non-Linear Empirical Models



## APPENDIX A

### Solids Retention Time (SRT) Calculations

The solids retention time for each reactor clarifier system is defined as the solids in the anoxic and aerobic reactors divided by the solids intentionally wasted and solids lost over the clarifier weir per day. Once the time requirement for equilibrium had elapsed, the system SRT during an investigative period was calculated for systems A, B, C, and D as illustrated in Table A1 and for system E as illustrated in Table A2. The daily SRT was calculated from the definition of SRT. The equilibrium SRT was determined from the age distribution function for a conservative substance in a complete mix reactor (Levenspiel, 1967). This relationship (Figure A1) shows that the operating period prior to 90% of equilibrium must exceed twice the system SRT.

### Analytical Procedures

#### Biochemical Oxygen Demand (BOD)

The five-day, 20°C BOD determinations were performed according to the method described in "Standard Methods", pages 489 to 495 (1971).

#### Filterable Organic Carbon (FOC)

Twenty microlitre samples previously acidified and purged were injected into a Beckman Infrared Carbon Analyzer. The resulting peaks were compared to a calibration curve prepared from standards using anhydrous potassium biphthalate.

#### Total Kjeldahl Nitrogen (TKN)

Total Kjeldahl nitrogen analyses (organic plus ammonia nitrogen) were performed according to Technicon Auto-Analyzer Industrial Method 146-71A. Essentially, this procedure consists of digestion of organic matter at 380°C followed by measurement of the ammonia produced using the Berthelot reaction in which the formation of a blue indophenol complex occurs when ammonia reacts with sodium phenate followed by the addition of sodium hypochlorite. Glycine standards were used for calibration. For keeping unfiltered samples homogenized in the sample cups, the system has two air aspirators. One aspirator mixes the next cup on the tray.



TABLE A1. SOLIDS RETENTION TIME CALCULATION FOR SYSTEM C - RUNS 52 AND 53

Date	Reactor MLSS Contents, g/L			Mean Plant Solids g	Intentional Wasting			†Unintentional Wasting g	Total Waste g	Daily System SRT days	Equilibrium System SRT days
	C1	C2	*C		Waste Vol. L	Waste Conc. g/L	Solids Waste g				
(1977)											
13/3											7
14/3	2.61	2.63	2.62	5 006.8	100.1	6.21	621.6	85.2	706.8	7.1	7.1
15/3	2.74	2.61	2.65	5 064.1	112.6	5.99	674.5	72.1	746.6	6.8	6.8
16/3	2.79	2.84	2.83	5 408.1	109.2	6.67	728.4	65.5	793.9	6.8	6.8
17/3	2.89	2.84	2.85	5 446.3	112.6	6.50	731.9	85.2	817.1	6.7	6.7

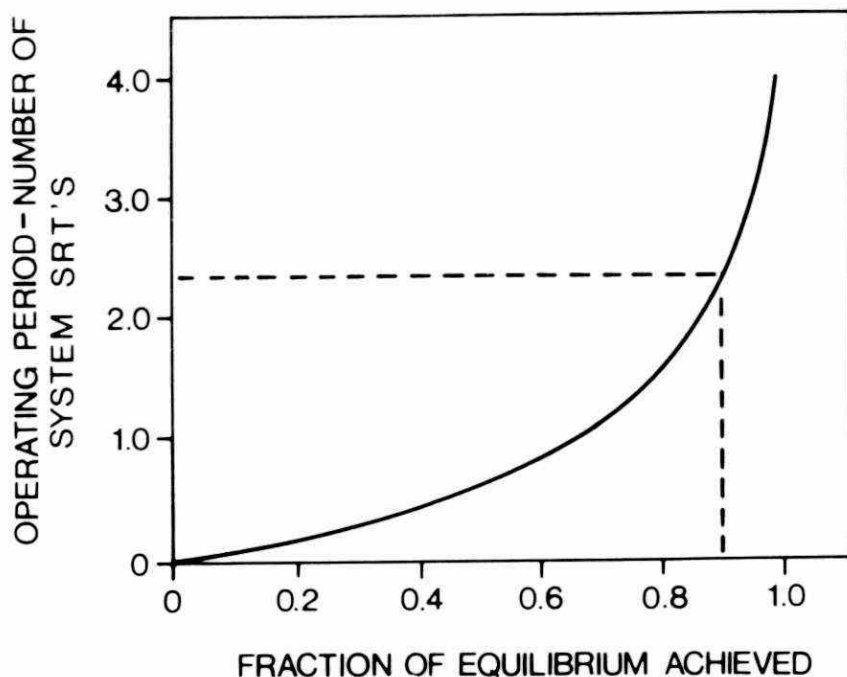
\* C is weighted MLSS according to C1 and C2 tank volumes.

† Unintentional wasting is solids lost over clarifier weir.

TABLE A2. SOLIDS RETENTION TIME CALCULATION FOR SYSTEM E - RUNS 52 AND 53

Date	Reactor MLSS Contents, g/L							Mean Plant Solids g	Intentional Wasting			Unintentional Wasting g	Total Waste g	Daily System SRT days	Equilibrium System SRT days
	E1	E2	E3	E4	E5	E6	*E		Waste Vol. L	Waste Conc. g/L	Solids Waste g				
(1977)															
13/3															7
14/3		4.00	3.06		2.77		3.45	11 059.3	254.3	6.29	1 599.8	196.6	1 796.4	6.2	6.4
15/3	4.03	2.97	2.76	3.97	2.94	2.73	3.42	10 775.7	215.2 45.5	6.09 3.47	1 310.7 157.9	275.2	1 743.8	6.2	6.2
16/3		3.90	2.84		2.66		3.32	10 460.7	218.4	6.09	1 330.1	196.6	1 526.7	6.9	6.7
17/3	3.83	2.82	2.51	3.92	2.87	2.53	3.27	10 303.1	195.7 45.5	5.86 3.34	1 146.5 152.0	262.1	1 560.6	6.6	6.6

\* E is weighted MLSS according to E1, E2, E3, E4, E5 and E6 tank volumes.



**FIGURE A1. THEORETICAL RELATIONSHIP  
BETWEEN EQUILIBRIUM AND PERIOD  
OF OPERATION**

#### Total Phosphorus

Analysis was carried out by Technicon methodology which involves digestion of organic material and measuring the orthophosphate. The quantitation of orthophosphate is achieved by reacting ammonium molybdate in an acid medium to form phosphormolybdic acid which is then reduced to molybdenum blue by reaction with amino-naphthol sulfonic acid reagent.

#### Ammonia

Analyses of ammonia nitrogen were conducted by Technicon Auto-Analyzer Industrial Method 98-70W. This is essentially the technique employed for total Kjeldahl nitrogen but with the omission of the selenium dioxide/sulphuric acid/perchloric acid digestion step which ammonifies the organic nitrogen fraction. Ammonium chloride standards provided calibration.

### Nitrite

Technicon Auto-Analyzer Industrial Method 100-70W was used for nitrite-nitrogen determinations. This technique involves a reaction between nitrite and sulphanilamide under acid conditions to form a diazo compound which in turn is coupled with N-1-naphthylethylenediamine to form a reddish purple azo dye. Colourimetric determination is then made on the sample.

### Nitrate Plus Nitrite

Nitrate plus nitrite-nitrogen analyses were performed by Technicon Auto-Analyzer Industrial Method 100-70W. In this method, the nitrate-nitrogen is reduced to nitrite in the copper-cadmium reduction column. The sample is then analyzed for nitrite nitrogen as described previously.

### Chemical Oxygen Demand (COD)

COD determinations were made according to the dichromate reflux method described in "Standard Methods" (1971). During the research period, a modified version of Technicon Auto-Analyzer Industrial Method 268-73W was adapted for COD analysis. The standards were first analyzed by the "Standard Methods" reflux technique and then analyzed on the Technicon equipment. The standard peaks produced on the Technicon system were then calibrated against the "Standard Methods" results.

### pH

pH was measured with an Orion Specific Ion Meter (Model 401) together with Fisher Combination electrodes (Cat. 13-639-90).

### Alkalinity

By using the Orion pH meter, 50 mL samples were titrated to a pH of 4.3 by addition of 0.02 N sulphuric acid. Results were expressed in mg/L as calcium carbonate.

### Suspended Solids

Gelman 0.3 micron glass fibre filters were dried, but not washed, for at least two hours in a 103°C oven. They were then cooled in a dessicator and weighed. Suspended solids determinations were made by filtering a minimum of 10 mL of solution through a filter. The filter was then re-dried at 103° for two or more hours, dessicated for 15 minutes and re-weighed. The increase in weight was taken as a measure of the suspended solids.

### Volatile Suspended Solids

This determination was made by igniting the glass fibre filter containing the residue from the suspended solids test in an electric muffle furnace at 550°C for 15 minutes. Following dessication, the filter was then re-weighed and the decrease in weight from the dried paper following the suspended solids determination was taken as a measure of the volatile suspended solids.

### Dissolved Oxygen

An Electronic Instruments Ltd., Dissolved Oxygen Meter Model 15A was used for dissolved oxygen determinations. It was found necessary to calibrate the probe about once every three weeks.

### Temperature

The DO meter also included a temperature probe and this was used for measurement of the feed stream and the reactor temperatures.

### Relationships for Filterable TKN Assimilated

The relationships derived describing the fraction of filterable TKN assimilated at the 7° to 8°C and 14° to 16°C temperature levels were, respectively:

$$\frac{R_i}{C_o} = 0.44e^{-0.05\theta_1}$$

and

$$\frac{R_i}{C_o} = 0.61e^{-0.14\theta_1}$$

### Determination of Aerobic SRT Required for Nitrification

In determining the aerobic SRT required for nitrification, the models describing the total fraction of filterable TKN removed and the fraction assimilated were compared at each temperature level. The SRT required for nitrification ( $\theta_{1c}$ ) was taken at the value of  $\theta_1$  where:

$$\frac{R'}{C_{O'}} = 2.0 \frac{R_1}{C_O}$$

For the 24° to 26°C temperature level, this occurs when:

$$\frac{R'}{C_{O'}} = 0.86, \text{ and}$$

$$\frac{R_1}{C_O} = 0.43$$

which corresponds to an aerobic SRT of 1.9.

For the 14° to 16°C temperature level, this occurs when:

$$\frac{R'}{C_{O'}} = 0.80, \text{ and}$$

$$\frac{R_1}{C_O} = 0.39$$

which corresponds to an aerobic SRT of 3.2.

For the 7° to 8°C temperature level, this occurs when:

$$\frac{R'}{C_{O'}} = 0.635, \text{ and}$$

$$\frac{R_1}{C_O} = 0.315$$

which corresponds to an aerobic SRT of 6.8.

### Computer Program for Parameter Determination for Linear and Non-Linear Empirical Models

The computer program used to determine the parameter values for the empirical models is presented in Table A3. An example of the calculation of the model parameters for the 7° to 8°C temperature level is also presented in Table A3. The results are presented in Figure 9.

TABLE A3. COMPUTER PROGRAM FOR PARAMETER DETERMINATION FOR LINEAR AND NON-LINEAR EMPIRICAL MODELS

```

PROGRAM SUTTON
DIMENSION X(54),Y(54),SCRAT(300)
DIMENSION TH(2),SIGNS(2),DIFF(2)
COMMON X
EXTERNAL MODEL
3 READ 4,NOB,TH(1),TH(2),JS
IF(IFECF(60).EQ.-1) STOP
DATA FOR PERCENT FILT TKN REMOVAL VS SPT(AEROBIC)
      PHASE ONE AND TWO DATA
4 FORMAT(I3,1X,F7.2,2X,F7.1,I3)
DO 10 I=1,NOB
READ 1000,Y(I),X(I)
1000 FORMAT(1X,F4.2,2X,F4.1)
10 PRINT 1000,Y(I),X(I)
PRINT 4,(NOB,TH(1),TH(2))
PRINT 6,JS
6 FORMAT(20X,14HPROBLEM NUMBER, I3)
SIGNS(1)=1
SIGNS(2)=1
DIFF(1)=.01
DIFF(2)=.01
EPS1=1.0E-7
EPS2=1.0E-7
CALL UWHAUS(1,MODEL,NOB,Y,2,TH,DIFF,SIGNS,EPS1,EPS2,
6 10,.01,10.,SCRAT)
GO TO 3
END

SUBROUTINE MODEL (NPROB,TH,F,NOB,NP)
COMMON X
DIMENSION TH(2),F(1),X(54)
DO 10 I=1,NOB
10 F(I)=(TH(1)*X(I))/(TH(2)+X(I))
RETURN
END

SUBROUTINE UWHAUS(NPROB,MODEL,NOB,Y,NP,TH,DIFF,SIGNS,EPS1,EPS2,
1 MIT,FLAM,FNU,SCRAT)
DIMENSION SCRAT(1)
IA=1
IB=IA+NP
IC=IB+NP
ID=IC+NP
IE=ID+NP
IF=IF+NP
IG=IF+NOB
IH=IG+NOB
II = IH + NP * NOB
IJ = IH
CALL HAUS59(NPROB,MODEL,NOB,Y,NP,TH,DIFF,SIGNS,EPS1,EPS2,MIT
1 .FLAM,FNU,SCRAT(IA), SCRAT(IB), SCRAT(IC), SCRAT(ID),
2 SCRAT(IE), SCRAT(IF), SCRAT(IG), SCRAT(IH), SCRAT(II),
3 SCRAT(IJ) )
RETURN
END

```



TABLE A3 (CONT'D). COMPUTER PROGRAM FOR PARAMETER DETERMINATION FOR LINEAR AND NON-LINEAR EMPIRICAL MODELS

```

SUBROUTINE HAUSS9(NPROB, MODEL, NOR, Y, NQ, TH, DIFZ, SIGNS, EP1S, EP2S,
1 MIT, FLAM, FNU, C.P.F.PHI, TP, F, R, A, D, DELZ)
      FORTRAN II VERSION
      H. J. HEDGECOCK
      ADAPTED FOR THE CDC 8400 (J. F. MACGREGOR)

      DIMENSION TH(NQ), DIFZ(NQ), SIGNS(NQ), Y(LRG)
      DIMENSION Q(NQ), R(NQ), E(NQ), PHI(NQ), TP(NQ)
      DIMENSION F(NQ), R(NQ)
      DIMENSION A(NQ,NQ), J(NQ,NQ), DELZ(NQ,NQ)
      DIMENSION TH(1), DIFZ(1), SIGNS(1), Y(1), Q(1), R(1), E(1),
1 PHI(1), TP(1), F(1), R(1), A(1), D(1), DELZ(1)
      ACOS(X) = ATAN(SORT(1.0/X**2 - 1.0))
      NP = NQ
      NPROB = NPROB
      NQD = NQ
      EPS1 = EP1S
      EPS2 = EP2S
      NPSQ = NP * NQ
      NSCPAQ = 5*NP+NPSQ + 2*NQD+NP*NQD
      PRINT 1000, 10000, NOR, D, 100000
      ENIN = 1001
      CALL GASSSO(1, NP, TH, TEMP, TEMP)
      PRINT 1002
      CALL GASSSO(1, NP, DIFZ, TEMP, TEMP)
      TP(MIN(10-1, 10-NP, NOR-NP, MIT-1, 99-10)) = 0.15, 15
      IF (FNU-1.0) 99, 99, 10
      GO TO 1000

      DO 10 I=1, NP
      TEMP = ABS(DIFZ(I))
      IF (ABS(IN1(1.0-TEMP, ABS(TH(I)))) 99, 99, 10
10 CONTINUE
      GA = FLAM
      NIT = 1
      LAOS = 0
      IF (EPS1) 5, 70, 70
      EPS1 = 0
      EPS2 = 0
      EPS3 = 0
      CALL MODEL(NPROB, TH, F, NOR, NQ)
      DO 50 I = 1, NOR
      R(I) = Y(I) - F(I)
      SSQ = SSQ + R(I)*R(I)
      SSQ = SSQ + 2*(I)*R(I)
      SSQ = SSQ - 1003, SSQ

                                          BEGIN ITERATION

100 GA = GA / FNU
      INTCNT = 0
      PRINT 100L, NIT
101 JS = 1 - NOR
      DO 120 J=1, NP
      TEMP = TH(J)
      P(J) = DIFZ(J)*TH(J)
      TH(J) = TH(J)+P(J)
      Q(J) = 0
      JS = JS + NOR
      CALL MODEL(NPROB, TH, DELZ(JS), NOR, NP)
      IU = JS-1
      DO 120 I = 1, NOR
      IU = IU + 1
      DELZ(IU) = DELZ(IU) - F(I)
120 Q(J) = Q(J) + DELZ(IU) * R(I)
      Q(J) = Q(J)/P(J)

```

Continued.... /

TABLE A3 (CONT'D). COMPUTER PROGRAM FOR PARAMETER DETERMINATION FOR LINEAR AND NON-LINEAR EMPIRICAL MODELS

```

                                NEXT*P (STEEPEST DESCENT)
130 TH(J) = TEMP
IF (LAOS) 131,131,414
131 DO 150 I = 1, NP
DO 151 J=1, I
SUM = 0
KJ = NOP*(J-1)
KI = NOP*(I-1)
DO 150 V = 1, NOB
KI = KI + 1
KJ = KJ + 1
150 SUM = SUM + DEL7(KI) * DEL7(KJ)
TEMP = SUM/(P(I)*P(J))
JI = J + NP*(I-1)
Q(JI) = TEMP
IJ = I + NP*(J-1)
151 Q(IJ) = TEMP
150 F(I) = SQRT(Q(JI))
666 CONTINUE
DO 153 I = 1, NP
IJ = I - NP
DO 153 J=1, I
IJ = IJ + NO
A(IJ) = Q(IJ) / (F(I)*F(J))
JI = J + NP*(I-1)
153 A(JI) = A(IJ)

                                A = SCALED MOMENT MATRIX

IT = - NP
DO 155 I=1, NP
P(I) = Q(I)/F(I)
PHI(I) = F(I)
IT = NO + 1 + IT
155 A(IT) = A(IT) + GA

I=1
CALL MATIN(A, NP, P, I, DET)

                                DZF = CORRECTION VECTOR

STEP=1.0
SUM1=0.
SUM2=0.
SUM3=0.
DO 231 I=1, NP
SUM1 = P(I)*PHI(I) + SUM1
SUM2 = P(I)*P(I) + SUM2
SUM3 = PHI(I) * PHI(I) + SUM3
231 PHI(I) = P(I)
TEMP = SUM1/SQRT(SUM2*SUM3)
TEMP = AMIN1(TEMP, 1.0)
TEMP = 87.235*ACOS(TEMP)
PRINT 1041, DET, TEMP

170 DO 220 I = 1, NP
P(I) = PHI(I) *STEP / F(I)
TR(I) = TH(I) + P(I)
220 CONTINUE
PRINT 7000
7000 FORMAT(20HTEST PRINT PARAMETER VALUES )
PRINT 2000, (TR(I), I = 1, NP)
DO 221 I = 1, NO
F(SIGN(I)) 221, 221, 222
222 F(SIGN(1.0,TH(I))*SIGN(1.0,TR(I))) 187, 221, 221
221 CONTINUE
SUMP=0
CALL MODEL(NPROC, TR, F, NOP, NP)
DO 230 I=1, NOB
R(I) = Y(I) - F(I)

```

Continued..../

TABLE A3 (CONT'D). COMPUTER PROGRAM FOR PARAMETER DETERMINATION FOR LINEAR AND NON-LINEAR EMPIRICAL MODELS

```

30 SUMR=SUMR+P(I)*P(I)
PRINT 1003, SUMR
IF (SUMR - (1.0+EPS1)*SSQ) 662, 662, 667
663 IF (AMIN1(TEMP-30.0, GA)) 665, 665, 666
65 STEP=STEP/2.0
INTCNT = INTCNT + 1
IF (INTCNT - 36) 170, 2700, 2700
664 GA=GA*FNU
INTCNT = INTCNT + 1
IF (INTCNT - 36) 666, 2700, 2700
662 PRINT 1007
DO 664 I=1, NP
66 TH(I)=TR(I)
CALL GASS60(1, NP, TH, TEMP, TEMP)
PRINT 1008, GA, SUMR
IF (EPS2) 223, 223, 225
223 IF (EPS1) 270, 270, 265
225 DO 240 I = 1, NP
IF (ABS(R(I))/(1.E-20+ABS(TH(I)))-EPS2) 240, 240, 241
241 IF (EPS1) 270, 270, 265
240 CONTINUE
PRINT 1009, EPS2
GO TO 280
265 IF (ABS(SUMR - SSQ) - EPS1*SSQ) 266, 266, 270
266 PRINT 1010, EPS1
GO TO 280
70 SSQ=SUMR
NIT=NT+1
IF (NIT - NIT) 100, 100, 260
2700 PRINT 2710
2710 FORMAT(//11E40*** THE SUM OF SQUARES CANNOT BE REDUCED TO THE SUM
OF SQUARES AT THE END OF THE LAST ITERATION - ITERATING STOPS //)
END ITERATION

260 PRINT 1011
PRINT 2001, (F(I), I = 1, NOB)
PRINT 1012
PRINT 2001, (R(I), I = 1, NOB)
SSQ=SUMP
IOF=NOB-NE
PRINT 1015
IF 0
CALL MATIN(0, NP, P, I, DET)
DO 7692 I=1, NP
IT = I + NP*(I-1)
7692 E(I) = SQRT(1/IT)
DO 340 I=1, NP
JT = I + NP*(I-1) - 1
IJ = I + NP*(I-2)
DO 340 J = I, NP
JT = JT + 1
A(JI) = D(JI) / (P(I)*E(J))
IJ = IJ + NP
340 A(IJ) = A(JI)
CALL GASS60(3, NP, TEMP, TEMP, A)
PRINT 1016
CALL GASS60(1, NP, E, TEMP, TEMP)
IF (IOF) 341, 410, 341
341 SDEV = SSQ / IOF
PRINT 1014, SDEV, IOF
SDEV = SQRT(SDEV)
DO 341 I=1, NP
P(I)=TH(I)+2.0*E(I)*SDEV

```

Continued..../

TABLE A3 (CONT'D). COMPUTER PROGRAM FOR PARAMETER DETERMINATION FOR LINEAR AND NON-LINEAR EMPIRICAL MODELS

```

91  TB(I)=TH(I)-2.0*E(I)*SQEV
   PRINT 1035
   CALL GASS60(2, NP, TP, P, TEMP)
   LAGS = 1
   GO TO 101
415  IF K = 1, NOR
      TEMP = 0
      DO 420 I=1,NP
      DO 420 J=1,NP
      ISUB = K+NOR*(I-1)
      PERUG1 = DELZ(ISUB)
      PERUG1 = DELZ(K + NOR*(I-1))
      JSUB = K+NOR*(J-1)
      PERUG2 = DELZ(JSUB)
      PERUG2 = DELZ(K + NOR*(J-1))
      IJ = I + NP*(J-1)
      PERUG3 = 0.0/(CIE7(I)*TH(I)*CIE7(J)*TH(J))
420  TEMP = TEMP + PERUG1 * PERUG2 * PERUG3
      TEMP = 2.0*SQRT(TEMP)*SQEV
      F(K)=F(K)+TEMP
415  F(K)=F(K)-TEMP
   PRINT 1038
   IE=0
   DO 430 I=1,NOR.5
   IF=IF+5
   IF(NOR-IF) 430.435,-13#
430  IE=NOR
435  PRINT 2001, (P(J), J = I, IE)
425  PRINT 2005, (F(J), J = I, IE)
410  PRINT 1033, NPF00
   RETURN
95  PRINT 1034
   GO TO 10
10000 FORMAT(38HNON-LINEAR ESTIMATION, PROBLEM NUMBER I3, // I5,
1  14H OBSERVATIONS, I5, 114H PARAMETERS I14, 174H SCRATCH REQUIRED)
1001  FORMAT(/25H0 INITIAL PARAMETER VALUES )
1002  FORMAT(/51H0 PROPORTIONS USED IN CALCULATING DIFFERENCE QUOTIENTS )
1003  FORMAT(/25H0 INITIAL SUM OF SQUARES = E12.4)
1004  FORMAT(///5X,13H ITERATION NO. I4)
1005  FORMAT(/32H0 PARAMETER VALUES VIA REGRESSION )
1006  FORMAT(///5X,13H APPROXIMATE CONFIDENCE LIMITS FOR EACH FUNCTION VAL
1UE )
1007  FORMAT(/52H0 ITERATION STOPS - RELATIVE CHANGE IN EACH PARAMETER LE
1SS THAN E12.4)
10100 FORMAT(/52H0 ITERATION STOPS - RELATIVE CHANGE IN SUM OF SQUARES LE
1SS THAN E12.4)
1011  FORMAT(22H1 FINAL FUNCTION VALUES )
1012  FORMAT(///5X,10H2 RESIDUALS )
1014  FORMAT(//24H0 VARIANCE OF RESIDUALS = ,E12.4,14,14,
120H DEGREES OF FREEDOM )
1015  FORMAT(///5X,15H0 CORRELATION MATRIX )
1016  FORMAT(///5X,21H0 NORMALIZING ELEMENTS )
1037  FORMAT(//13H0 END OF PROBLEM NO. I3)
1034  FORMAT(/15H0 PARAMETER ERROR )
10350 FORMAT(/71H0 INDIVIDUAL CONFIDENCE LIMITS FOR EACH PARAMETER (ON LI
1NEAR HYPOTHESIS) )
10400 FORMAT(/38H0 LAMDA = E10.3,40X,33H SUM OF SQUARES AFTER REGRESSION =
1E15.7)
1041  FORMAT(14H DETERMINANT = E12.4, 6X, 25H ANGLE IN SCALED COORD. =
1E5.2, 3H DEGREES )
1047  FORMAT(23H0 TEST POINT SUM OF SQUARES = E12.4)
2001  FORMAT(/5E12.4)
2005  FORMAT(5E12.4)
   END

```

Continued..../

TABLE A3 (CONT'D). COMPUTER PROGRAM FOR PARAMETER DETERMINATION FOR LINEAR AND NON-LINEAR EMPIRICAL MODELS

```

SUBROUTINE MATIN(A, NVAR, R, NR, DET)
  DIMENSION A(NVAR, 1), P(NVAR, 1)
  COMMON/CASPAR/DUMIES(7), PIVOTM
  PIVOTM = A(1,1)
  DET = 1.0
  DO 350 ICOL = 1, NVAR
    PIVOT = A(ICOL, ICOL)
    PIVOTM = AMIN1(PIVOT, PIVOTM)
    DET = PIVOT * DET

  DIVIDE PIVOT ROW BY PIVOT ELEMENT
    A(ICOL, ICOL) = 1.0

  PIVOT = AMAX1(PIVOT, 1.E-20)
  PIVOT = A(ICOL, ICOL)/PIVOT
  DO 370 L=1, NVAR
    A(ICOL, L) = A(ICOL, L)*PIVOT
    IF (NR.EQ. 0) GO TO 371
  DO 370 L=1, NR
    P(ICOL, L) = P(ICOL, L)*PIVOT

  REDUCE NON-PIVOT ROWS
  DO 371 L1=1, NVAR
    IF (L1.EQ. ICOL) GO TO 380
    T = A(L1, ICOL)
    A(L1, ICOL) = 0.
    DO 380 L=1, NVAR
      A(L1, L) = A(L1, L) - A(ICOL, L)*T
      IF (NR.EQ. 0) GO TO 380
    DO 380 L=1, NR
      P(L1, L) = P(L1, L) - P(ICOL, L)*T
  380 CONTINUE
  RETURN
END

SUBROUTINE GASS60(ITYPE, NO, A, R, C)
  DIMENSION A(NO), P(NO), C(NO, NO)
  NR = NO
  NR = NR/10
  LOW = 1
  LUP = 10
  IF (NR) 15, 20, 30
  RETURN
  LUP=NR
  IF (LOW.GT. LUP) RETURN
  30 PRINT 500, (J, J=LOW, LUP)
  GO TO (-0, 50, 80), ITYPE
  40 PRINT 500, (A(J), J=LOW, LUP)
  GO TO 100
  60 PRINT 500, (P(J), J=LOW, LUP)
  GO TO 10
  DO 90 I=LOW, LUP
  90 PRINT 70, I, (C(J, I), J=LOW, I)
  LOW2=LUP+1
  IF (LOW2.GT. NR) GO TO 100
  DO 35 I=LOW2, NR
  35 PRINT 720, I, (C(J, I), J=LOW, LUP)
  100 LOW = LOW + 10
  LUP = LUP + 10
  NR = NR - 1
  GO TO 10
  300 FORMAT(/I4, 3I12)
  500 FORMAT(10E12.4)
  720 FORMAT(140, I3, 1X, F7.4, 9E12.4)
  CONTINUE
  RETURN
END
FINIS

```

Continued.... /

TABLE A3 (CONT'D). COMPUTER PROGRAM FOR PARAMETER DETERMINATION FOR LINEAR AND NON-LINEAR EMPIRICAL MODELS

Output from computer program for parameter determination for linear and non-linear empirical model:

% FILT TKN REMOVAL / SRT (AEROBIC)

0.67	14.1
0.35	14.1
0.02	10.0
0.74	10.0
0.74	10.0
0.71	10.0
0.73	14.3
0.26	14.3
0.85	10.2
0.08	10.2
0.02	14.3
0.03	14.3
0.04	14.3
0.03	14.3
0.03	14.3
0.07	3.1
0.07	3.1
0.04	0.0
0.00	4.0
0.39	0.0
0.03	12.0
0.03	12.0
0.07	15.0
0.70	7.1
0.02	7.1
0.02	7.1
0.00	6.7
0.72	7.1
0.20	2.1
0.17	1.0
0.21	2.0
0.47	0.0
0.05	13.0
0.04	14.0
0.07	13.0
0.08	0.0
0.00	2.1
0.11	7.8
0.06	7.4
0.00	0.0
0.07	14.3
0.78	14.3
0.17	1.4
0.03	2.1
0.03	2.1
0.07	2.3
0.31	2.0
0.07	3.2
0.07	11.5
0.35	10.7
0.00	13.0
0.70	14.0
0.00	15.0
0.30	0.30

2.5 PROBLEM NUMBER 60

Continued.... /

TABLE A3 (CONT'D). COMPUTER PROGRAM FOR PARAMETER DETERMINATION FOR LINEAR AND NON-LINEAR EMPIRICAL MODELS

NON-LINEAR ESTIMATION, PROBLEM NUMBER 1

12 OBSERVATIONS, 2 PARAMETERS

222 GOTOCH REQUIRED

INITIAL PARAMETER VALUES

$0.1000E+00$   $0.2500E+01$

PROPORTIONS USED IN CALCULATING DIFFERENCE QUOTIENTS

$0.1000E-01$   $0.1000E-01$

INITIAL SUM OF SQUARES =  $0.1193E+01$

DETERMINANT =  $0.1677E+00$  ITERATION NO. 1  
ANGLE IN SCALED COORD. =  $16.590$  DEGREES

TEST POINT PARAMETER VALUES  
 $0.1054E+01$   $0.4348E+01$

TEST POINT SUM OF SQUARES =  $0.1072E+01$

PARAMETER VALUES VIA REGRESSION

$0.1053E+01$   $0.4348E+01$

LAMBDA =  $0.100E-02$  SUM OF SQUARES AFTER REGRESSION =  $0.1071949E+01$

DETERMINANT =  $0.9051E-01$  ITERATION NO. 2  
ANGLE IN SCALED COORD. =  $32.430$  DEGREES

TEST POINT PARAMETER VALUES  
 $0.1107E+01$   $0.5009E+01$

TEST POINT SUM OF SQUARES =  $0.1067E+01$

PARAMETER VALUES VIA REGRESSION

$0.1107E+01$   $0.5009E+01$

LAMBDA =  $0.100E-03$  SUM OF SQUARES AFTER REGRESSION =  $0.1066376E+01$

Continued..../

TABLE A3 (CONT'D). COMPUTER PROGRAM FOR PARAMETER DETERMINATION FOR LINEAR AND NON-LINEAR EMPIRICAL MODELS

[illegible]

Continued.../



TABLE A3 (CONT'D). COMPUTER PROGRAM FOR PARAMETER DETERMINATION FOR LINEAR AND NON-LINEAR EMPIRICAL MODELS

RESIDUALS

-0.1473E+00	-0.6701E-01	0.1825E+00	0.2545E-02	0.2545E-02
-0.2745E-01	-0.9003E-01	0.3397E-01	0.1077E+00	0.1377E+00
0.6997E-01	0.1100E+00	0.1397E-01	0.5997E-01	0.1798E+00
0.1769E+00	-0.8395E-01	-0.3081E-01	-0.2025E+00	-0.1510E+00
-0.1510E+00	0.1266E+00	0.1413E+00	0.2713E+00	0.2713E+00
-0.4384E-01	-0.1434E+00	-0.1263E+00	-0.1333E+00	-0.1052E+00
-0.2750E+00	0.5078E-01	0.2452E-01	0.1395E+00	0.1490E+00
0.1513E+00	0.3619E-01	-0.9082E-01	-0.1324E+00	-0.1500E+00
-0.4003E-01	-0.7123E-01	0.1433E+00	0.1237E+00	0.1223E+00
-0.5217E-02	-0.4659E-01	-0.2391E+00	-0.4040E+00	0.1008E+00
-0.2544E-01	0.1099E+00			

CORRELATION MATRIX

	1	2
1	1.0000	
2	0.3617	1.0000

NORMALIZING ELEMENTS

1	2
0.9033E+00	0.1073E+02

VARIANCE OF RESIDUALS = 0.2134E-01, 50 DEGREES OF FREEDOM

INDIVIDUAL CONFIDENCE LIMITS FOR EACH PARAMETER (ON LINEAR HYPOTHESIS)

1	2
0.1324E+01	0.6170E+01
0.8740E+00	0.1900E+01

Continued..../

TABLE A3 (CONT'D). COMPUTER PROGRAM FOR PARAMETER DETERMINATION FOR LINEAR AND NON-LINEAR EMPIRICAL MODELS

APPROXIMATE CONFIDENCE LIMITS FOR EACH FUNCTION VALUE

[illegible]

END OF PROBLEM NO. 1

2109

## APPENDIX B

System Operating Conditions and Analytical Results

Pilot Plant Nitrification Batch Experimental Procedures

Calculation of Maximum Ammonia Oxidation Rates from Batch Nitrification Results: Procedure

Pilot Plant Denitrification Batch Experiments

Calculation of Denitrification Rates from Pilot Plant Batch Denitrification Results

Denitrification Batch Experiments to Assess Methanol and Sewage as Carbon Sources and to Assess Rates Under Carbon and Non-Carbon Limiting Conditions

Organic Carbon Requirements for Denitrification in Single Sludge Systems

## APPENDIX B

### System Operating Conditions and Analytical Results

Tables B1 and B2 contain, respectively, the experimental operating conditions and the analytical results for the continuous runs completed in Phases 1 and 2.

The abbreviations and symbols used in Tables B1 and B2 and in the rest of the report are interpreted in Appendix C.

### Pilot Plant Nitrification Batch Experimental Procedures

The nitrification batch experiments were carried out in the pilot plant aerobic reactors (A1, B1, and C2) immediately following completion of certain continuous runs. Ammonia in the form of  $\text{NH}_4\text{Cl}$  was added to the reactor to increase the ammonia-N concentration to a value greater than or equal to 10 mg/L N. Alkalinity as  $\text{CaCO}_3$  was added in sufficient quantities in accord with the stoichiometric equations (1 and 2). The batch test began after 10 minutes had elapsed to ensure mixing of the added chemicals. The results of the experiments appear in Table B3.

### Calculation of Maximum Ammonia Oxidation Rates from Batch Nitrification Results: Procedure

This procedure first involved the determination of the maximum ammonia oxidation rate (Table B3, Figure B1) for each batch test based on total volatile suspended solids ( $K_{AV}^*$ ). The ammonia oxidation rate is calculated from the slope of the linear least squares straight line on the basis of the filterable TKN results (Figure B1). The aerobic SRT of the reactor from which the batch results were derived was then compared to the critical aerobic SRT ( $\theta_{1c}$ ) for nitrification, previously determined according to the Arrhenius or modified Arrhenius relationships (Table 4).

TABLE B1. PHASE 1 AND PHASE 2 EXPERIMENTAL OPERATING CONDITIONS FOR CONTINUOUS RUNS

Run No.	Date	System	Reactor Temp., °C		Reactor SRT's, days			*Nominal Reactor HRT's, hrs.		Reactor MLVSS mg/L <sup>-1</sup>		Methanol Addition to Anoxic Reactor mg COD/L of feed
			Aerobic	Anoxic	Aerobic (θ <sub>1</sub> )	Anoxic (θ <sub>2</sub> )	System (θ)	Aerobic	Anoxic	<sup>+</sup> System	Anoxic	
PHASE 1												
P1-1	(1976) 25/5	D	15	15=	4.3	1.7	6	5.0	2.0	3 212		
P1-2	27/5	D	15	15	4.3	1.7	6	5.0	2.0	3 214		
P1-3	8/6	A	25.0	25.0	4.0	6.0	10	4.0	6.0	1 972		
"	"	B	26.5	26.0	2.8	1.2	4	5.0	2.0	703		**
"	"	C	26.0	26.0	2.1	0.9	3	5.0	2.0	1 339	1 303	280
P1-4	10/6	A	26.5	26.0	4.0	6.0	10	4.0	6.0	2 132		
"	"	B	26.5	27	2.8	1.2	4	5.0	2.0	1 154		**
"	"	C	25.0	26.0	2.1	0.9	3	5.0	2.0	1 282	1 318	280
P1-5	22/6	A	15.0	16.0	7.2	10.8	18	4.0	6.0	2 450		
"	"	B	16.0	16.0	2.8	1.2	4	5.0	2.0	1 894	1 915	155
"	"	C	15.0	15.0	4.3	1.7	6	5.0	2.0	2 340	2 340	280
P1-6	24/6	A	15.0	15.0	7.2	10.8	18	4.0	6.0	2 800		
"	"	B	15.0	15.0	2.8	1.2	4	5.0	2.0	1 993	1 913	155
"	"	C	15.0	15.0	4.3	1.7	6	5.0	2.0	2 776	2 619	280
P1-7	1/7	C	15.0	15.0	2.8	0.7	3	5.5	1.5	1 342	1 385	280

\* Nominal HRT's based on feed rate of sewage.

\*\* Methanol addition rate indeterminate.

† This is the weighted mean VSS in the system. The weighting is according to reactor volume.

Cont'd...../

TABLE B1 (CONT'D). PHASE 1 AND PHASE 2 EXPERIMENTAL OPERATING CONDITIONS FOR CONTINUOUS RUNS

Run No.	Date	System	Reactor Temp., °C		Reactor SRT's, days			*Nominal Reactor HRT's, hrs.		Reactor MLVSS mg/L <sup>-1</sup>		Methanol Addition to Anoxic Reactor mg COD/L of feed
			Aerobic	Anoxic	Aerobic ( $\theta_1$ )	Anoxic ( $\theta_2$ )	System ( $\theta$ )	Aerobic	Anoxic	†System	Anoxic	
P1-8	6/7	A	14.5	15.0	4.8	7.2	12	4.0	6.0	2 390		
"	"	B	15.0	15.0	2.1	0.9	3	5.0	2.0	1 087	1 118	155
P1-9	8/7	A	14.5	15.0	4.8	7.2	12	4.0	6.0	2 524		
"	"	B	15.0	15.0	2.1	0.9	3	5.0	2.0	896	1 189	155
"	"	C	15.0	15.0	2.1	0.9	3	5.0	2.0	1 793	1 959	280
P1-10	14/7	A	14.5	14.5	4.0	8.0	12	3.33	6.67	2 455		
"	"	B	15.0	15.0	1.4	1.6	3	4.67	2.33	1 200	1 232	155
"	"	C	15.0	14.0	2.7	1.3	4	4.67	2.33	1 530	1 517	280
"	16/7	C	15.0	15.0	3.0	1.0	4	4.67	2.33	1 585	1 585	280
P1-12	20/7	A	14.5	15.0	5.0	5.0	10	5.0	5.0	2 795		
"	"	B	15.0	15.0	2.3	0.7	3	5.25	1.76	1 428	1 440	155
"	"	C	15.5	15.0	2.5	1.0	3	5.0	2.0	1 659	1 730	280
P1-13	5/8	B	8.0	8.5	7.1	2.9	10	5.0	2.0	3 323	3 364	155
"	"	C	8.0	8.0	9.9	4.1	14	5.0	2.0	4 394	4 380	280
P1-14	10/8	A	8.0	8.5	8.4	12.6	21	4.0	6.0	3 436		
"	"	B	8.0	8.0	7.1	2.9	10	5.0	2.0	3 507	3 331	155
"	"	C	7.5	7.5	7.1	2.9	10	5.0	2.0	4 985	5 010	280
P1-15	12/8	A	7.0	7.0	8.4	12.6	21	4.0	6.0	3 638		
"	"	B	8.0	8.0	7.1	2.9	10	5.0	2.0	3 594	3 460	155
"	"	C	8.5	9.0	7.8	3.2	11	5.0	2.0	4 936	4 925	280

\* Nominal HRT's based on feed rate of sewage.

† This is the weighted mean VSS in the system. The weighting is according to reactor volume.

Cont'd...../

TABLE B1 (CONT'D). PHASE 1 AND PHASE 2 EXPERIMENTAL OPERATING CONDITIONS FOR CONTINUOUS RUNS

Run No.	Date	System	Reactor Temp., °C		Reactor SRT's, days			*Nominal Reactor HRT's, hrs.		Reactor MLVSS mg/L <sup>-1</sup>		Methanol Addition to Anoxic Reactor mg COD/L of feed
			Aerobic	Anoxic	Aerobic ( $\theta_1$ )	Anoxic ( $\theta_2$ )	System ( $\theta$ )	Aerobic	Anoxic	†System	Anoxic	
P1-16	17/8	A	6.0	6.5	6.6	13.4	20	3.33	6.67	3 272		
"	"	B	6.5	7.0	6.7	3.3	10	4.67	2.33	3 253	3 189	155
"	"	C	7.5	7.0	7.4	3.6	11	4.67	2.33	5 130	4 781	280
P1-17	20/8	B	8.0	8.0	7.5	2.5	10	4.67	2.33	3 780	3 696	155
"	"	C	8.0	7.5	9.8	3.2	13	5.25	1.75	4 536	4 403	280
P1-18	3/9	C	15.0	14.0	1.4	0.6	2	5.0	2.0	1 173	874	280
P1-19	8/9	A	14.5	14.5	2.8	4.2	7	4.0	6.0	1 832		
"	"	B	15.0	15.0	1.4	0.6	2	5.0	2.0	919		155
"	"	C	15.0	15.0	0.7	0.3	1	5.0	2.0	957	971	280
P1-20	21/9	A	25.0	24.5	1.2	1.8	3	4.0	6.0	950		
"	"	B	25.0	25.0	1.1	0.4	1.5	5.0	2.0	674	727	155
"	"	C	25.0	25.0	1.4	0.6	2	5.0	2.0	803	761	280
P1-21	28/9	A	25.0	24.0	1.5	1.5	3	5.0	5.0	1 005		
"	"	B	25.0	25.0	1.1	0.4	1.5	5.25	1.75	940	876	155
"	"	C	25.0	25.0	1.5	0.5	2	5.25	1.75	682	578	280
P1-22	1/10	A	25.0	24.5	1.0	2.0	3	3.33	6.67	1 197		
"	"	B	25.0	25.0	1.0	0.5	1.5	4.67	2.33	763	793	155
"	"	C	25.5	25.0	1.3	0.7	2	4.67	2.33	1 170	990	280
P1-23	7/10	B	25.0	25.0	1.4	0.6	2	5.0	2.0	869	924	155
P1-24	12/10	B	25.0	25.0	1.8	0.7	2.5	5.0	2.0	871	882	155

\* Nominal HRT's based on feed rate of sewage.

† This is the weighted mean VSS in the system. The weighting is according to reactor volume.

Cont'd...../

TABLE B1 (CONT'D). PHASE 1 AND PHASE 2 EXPERIMENTAL OPERATING CONDITIONS FOR CONTINUOUS RUNS

Run No.	Date	System	Reactor Temp., °C		Reactor SRT's, days			*Nominal Reactor HRT's, hrs.		Reactor MLVSS mg/L <sup>-1</sup>		Methanol Addition to Anoxic Reactor mg COD/L of feed
			Aerobic	Anoxic	Aerobic ( $\theta_1$ )	Anoxic ( $\theta_2$ )	System ( $\theta$ )	Aerobic	Anoxic	† System	Anoxic	
P1-25	19/10	A	25.0	24.0	6.8	10.2	17	4.0	6.0	3 218		
"	"	B	24.5	24.0	3.6	1.4	5	5.0	2.0	1 899		155
"	"	C	23.0	23.5	2.8	1.2	4	5.0	2.0	2 023	1 935	280
P1-26	21/10	A	25.5	25.0	6.4	9.6	16	4.0	6.0	3 066		
"	"	B	25.0	25.0	3.6	1.4	5	5.0	2.0	1 761		155
"	"	C	24.0	25.0	2.8	1.2	4	5.0	2.0	1 770	1 807	280
P1-27	26/10	A	25.0	24.5	7.5	7.5	15	5.0	5.0	3 045		
"	"	B	25.0	25.0	3.4	1.1	4.5	5.25	1.75	1 505		155
"	"	C	25.0	26.0	3.0	1.0	4	5.25	1.75	2 173	2 055	280
P1-28	29/10	B	25.0	25.0	3.0	1.5	4.5	4.67	2.33	1 485	1 657	155
"	"	C	24.5	25.0	2.7	1.3	4	4.67	2.33	2 157	2 170	280
P1-29	16/11	B	14.5	15.0	0.7	0.3	1	5.0	2.0	973	893	155
P1-30	17/11	B	15.0	15.0	0.7	0.3	1	5.0	2.0	843	987	155
P1-31	24/11	C	7.0	6.5	2.1	0.9	3	5.0	2.0	2 183	1 903	280
P1-32	25/11	C	7.0	7.0	2.1	0.9	3	5.0	2.0	1 943	1 822	280
P1-33	30/11	C	7.0	7.0	2.3	0.7	3	5.25	1.75	2 103	2 220	280
P1-34	3/12	A	7.5	8.5	4.0	6.0	10	4.0	6.0	3 040		
"	"	B	6.0	7.0	2.1	0.9	3	5.0	2.0	1 667	1 706	155
"	"	C	7.5	7.5	2.0	1.0	3	4.67	2.33	2 133	2 197	280
P1-35	10/12	A	7.0	8.0	5.0	5.0	10	5.0	5.0	2 295		
"	"	B	6.0	6.5	1.9	0.6	2	5.25	1.75	1 270	1 441	155

\* Nominal HRT's based on feed rate of sewage.

† This is the weighted mean VSS in the system. The weighting is according to reactor volume.

Cont'd...../



TABLE B1 (CONT'D). PHASE 1 AND PHASE 2 EXPERIMENTAL OPERATING CONDITIONS FOR CONTINUOUS RUNS

Run No.	Date	System	Reactor Temp., °C		Reactor SRT's, days			*Nominal Reactor HRT's, hrs.		Reactor MLVSS mg/L <sup>-1</sup>		Methanol Addition to Anoxic Reactor mg COD/L of feed
			Aerobic	Anoxic	Aerobic ( $\theta_1$ )	Anoxic ( $\theta_2$ )	System ( $\theta$ )	Aerobic	Anoxic	<sup>†</sup> System	Anoxic	
PI-36	14/12	B	7.0	7.5	2.0	1.0	3	4.67	2.33	1 787	1 867	155
PI-37	21/12	C	7.5	7.0	9.2	3.8	13	5.0	2.0	4 339	4 211	280
PI-38	28/12	C	7.0	7.0	11.4	4.6	16	5.0	2.0	4 734	4 570	140
	(1977)											
PI-39	4/1	A	8.0	7.5	12.0	18.0	30	5.0	7.5	5 132		
"	"	B	6.0	6.5	9.9	4.1	14	5.95	2.38	3 923	3 710	121
"	"	C	7.5	7.5	10.7	4.3	15	6.25	2.5	4 226	4 224	140
PI-40	6/1	A	8.5	8.0	12.0	18.0	30	5.0	7.5	4 950		
PI-41	25/1	B	7.0	8.0	13.0	7.0	20	5.55	2.78	3 863	3 787	121
"	"	C	7.5	7.0	13.0	7.0	20	5.9	2.9	4 693	4 428	140
PI-42	28/1	B	7.0	7.0	14.0	6.0	20	5.95	2.38	3 536	3 682	121
"	"	C	7.0	7.0	14.0	6.0	20	5.9	2.9	4 795	4 795	140
PI-43	1/2	A	7.5	8.0	16.0	16.0	32	6.25	6.25	4 327		
"	"	B	7.5	7.0	15.0	5.0	20	6.25	2.08	3 700	3 786	121
"	"	C	7.5	7.0	15.0	5.0	20	6.6	2.2	4 303	4 290	140
PI-44	8/2	A	7.0	7.5	14.1	20.9	35	5.00	7.50	4 605		
"	"	B	7.5	8.0	14.3	5.7	20	5.95	2.38	3 633	3 633	61
"	"	C	7.0	7.0	14.3	5.7	20	6.25	2.5	4 700	4 772	70
PI-45	10/2	B	7.5	8.0	14.3	5.7	20	5.95	2.38	3 633	3 638	61
"	"	C	8.0	7.5	14.3	5.7	20	6.25	2.5	4 684	4 668	70

\* Nominal HRT's based on feed rate of sewage.

† This is the weighted mean VSS in the system. The weighting is according to reactor volume.

Cont'd...../

TABLE B1 (CONT'D). PHASE 1 AND PHASE 2 EXPERIMENTAL OPERATING CONDITIONS FOR CONTINUOUS RUNS

Run No.	Date	System	Reactor Temp., °C		Reactor SRT's, days			Nominal Reactor HRT's, hrs.		Reactor MLVSS mg/L <sup>-1</sup>		Methanol Addition to Anoxic Reactor mg COD/L of feed
			Aerobic	Anoxic	Aerobic ( $\theta_1$ )	Anoxic ( $\theta_2$ )	System ( $\theta$ )	Aerobic	Anoxic	<sup>†</sup> System	Anoxic	
P1-46	11/2	A	6.5	7.0	14.1	20.9	35	5.00	7.50	4 804		
"	"	C	8.0	8.0	14.3	5.7	20	6.25	2.5	4 965	4 668	70
PHASE 2												
P2-47	15/2	D	7.5	7.0	14.3	5.7	20	6.25	2.5	4 774		
P2-48	17/2	D	7.0	7.0	14.3	5.7	20	6.25	2.5	4 772		
P2-49	18/2	D	7.5	7.0	14.3	5.7	20	6.25	2.5	4 584		
P2-50	8/3	D	14.5	14.5	5.0	2.0	7	5.0	2.0	1 774		
P2-51	10/3	A	15.5	16.0	6.0	12.0	18	3.33	6.67	3 357		
"	"	D	15.0	15.0	5.0	2.0	7	5.0	2.0	1 912		
"	"	E	15.5	15.5	5.1	1.9	7	*6.73	*1.97	2 301		
P2-52	15/3	A	14.5	14.5	5.7	11.3	17	3.33	6.67	3 349		
"	"	C	15.0	15.0	5.0	2.0	7	5.0	2.0	1 853	1 952	70
"	"	E	15.0	15.0	4.7	1.8	6.5	6.73	1.97	2 388		
P2-53	17/3	C	15.0	15.0	5.0	2.0	7	5.0	2.0	2 038	2 074	70
"	"	E	15.0	15.0	4.7	1.8	6.5	6.73	1.97	2 272		
P2-54	1/4	A	24.0	23.5	2.9	7.1	10	2.9	7.1	1 753		
"	"	E	25.0	25.0	2.9	1.1	4.0	6.73	1.97	1 269		
P2-55	5/4	A	24.0	24.0	2.9	7.1	10	2.9	7.1	1 889		
"	"	C	24.0	25.0	2.5	1.0	3.5	5.0	2.0	1 233	1 221	92
"	"	E	25.5	25.5	2.9	1.1	4	6.73	1.97	1 238		

\* Nominal HRT's based on feed rate of sewage.

† This is the weighted mean VSS in the system. The weighting is according to reactor volume.

Cont'd...../

TABLE B1 (CONT'D). PHASE 1 AND PHASE 2 EXPERIMENTAL OPERATING CONDITIONS FOR CONTINUOUS RUNS

Run No.	Date	System	Reactor Temp., °C		Reactor SRT's, days			Nominal Reactor HRT's, hrs.		Reactor MLVSS mg/L <sup>-1</sup>		Methanol Addition to Anoxic Reactor mg COD/L of feed
			Aerobic	Anoxic	Aerobic ( $\theta_1$ )	Anoxic ( $\theta_2$ )	System ( $\theta$ )	Aerobic	Anoxic	†System	Anoxic	
P2-56	7/4	C	24.0	24.0	2.5	1.0	3.5	5.0	2.0	1 181	1 169	92
"	"	E	26.0	26.0	2.9	1.1	4	6.73	1.97	1 212		
P2-57	13/4	A	25.0	24.5	2.0	8.0	10	2.0	8.0	1 779		
"	"	D	24.5	25.0	2.5	1.0	3.5	5.0	2.0	1 208		
"	"	E	25.0	25.0	2.9	1.1	4	6.73	1.97	1 430		
P2-58	15/4	A	24.0	23.5	2.0	8.0	10	2.0	8.0	1 863		
"	"	D	22.0	22.0	2.5	1.0	3.5	5.0	2.0	1 267		
"	"	E	25.0	25.0	2.9	1.1	4	6.73	1.97	1 381		
P2-59	19/4	C	24.5	25.0	2.5	1.0	3.5	5.0	2.0	1 598	1 513	70
P2-60	5/5	A	8.0	8.0	10.0	10.0	20	5.0	5.0	2 821		
"	"	E	7.5	7.5	10.2	4.8	15	6.73	1.97	4 624		
P2-61	10/5	A	8.0	8.0	10.0	10.0	20	5.0	5.0	2 694		
"	"	E	7.0	7.0	10.2	4.8	15	6.73	1.97	4 715		
P2-62	13/5	D	16.0	16.0	5.0	8.0	13	3.10	5.0	2 771		
P2-63	17/5	D	15.5	15.5	3.8	6.2	10	3.10	5.0	2 483		
"	"	E	6.5	7.0	13.0	5.0	18	6.73	1.97	4 744		*70
P2-64	19/5	A	8.0	8.0	10.0	15.0	25	4.0	6.0	3 156		
"	"	E	7.0	7.5	11.6	4.4	16	6.73	1.97	4 577		70
P2-65	25/5	A	8.0	8.5	10.0	15.0	25	4.0	6.0	3 636		
"	"	D	17.0	17.0	6.3	7.2	13.5	4.4	5.0	2 612		

\* Nominal HRT's based on feed rate of sewage.

† This is the weighted mean VSS in the system. The weighting is according to reactor volume.

Cont'd...../

TABLE B1 (CONT'D). PHASE 1 AND PHASE 2 EXPERIMENTAL OPERATING CONDITIONS FOR CONTINUOUS RUNS

Run No.	Date	System	Reactor Temp., °C		Reactor SRT's, days			*Nominal Reactor HRT's, hrs.		Reactor MLVSS mg/L <sup>-1</sup>		Methanol Addition to Anoxic Reactor mg COD/L of feed
			Aerobic	Anoxic	Aerobic ( $\theta_1$ )	Anoxic ( $\theta_2$ )	System ( $\theta$ )	Aerobic	Anoxic	†System	Anoxic	
P2-66	10/6	A	15.5	15.5	5.7	11.3	17	3.33	6.67	3 398		70
"	"	D	15.0	15.0	5.6	6.4	12	4.4	5.0	3 049		
"	"	E	15.0	15.5	5.8	2.2	8	6.73	1.97	3 730		
P2-67	14/6	A	15.0	15.5	5.7	11.3	17	3.33	6.67	3 321		70
"	"	D	15.0	15.0	5.6	6.4	12	4.4	5.0	3 011		
"	"	E	15.0	15.0	5.5	2.0	7.5	6.73	1.97	3 662		
P2-68	16/6	A	15.0	15.5	6.0	12.0	18	3.33	6.67	3 236		70
"	"	D	16.0	15.5	5.6	6.4	12	4.4	5.00	3 005		
"	"	E	15.0	15.0	5.5	2.0	7.5	6.73	1.97	3 561		
P2-69	21/6	A	15.0	15.5	6.0	12.0	18	3.33	6.67	3 279		70
"	"	D	15.0	15.0	5.6	6.4	12	4.4	5.00	3 160		

\* Nominal HRT's based on feed rate of sewage.

† This is the weighted mean VSS in the system. The weighting is according to reactor volume.

TABLE B2. ANALYTICAL RESULTS FOR CONTINUOUS RUNS (ALL VALUES IN  $\text{mg}\cdot\text{L}^{-1}$ )  
SYSTEM A

Run No.	Feed						System	Aerobic Reactor				Effluent										
	Unfiltered		Filtered				Weighted Mean MLSS Unfiltered TKN	Filtered				Unfiltered				Filtered						
	COD	Alk	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N		NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N	NO <sub>2</sub> <sup>-</sup> -N	TKN	Alk	SS	TP	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N	NO <sub>2</sub> <sup>-</sup> -N	TP	
P1-3	293	284	105	17.0	19.9	0.2	35	0.8	1.1	10.9	0.0	1.9	191	7	-	21	0.8	1.5	4.5	1.3	-	
P1-4	264	282	92	16.0	17.9	0.0	89.5	1.0	1.6	10.3	0.1	1.4	200	9	-	38	0.8	1.0	3.9	0.3	-	
P1-5	310	250	113	18.0	19.5	0.3	142.0	0.8	1.3	10.0	0.2	3.0	188	17	-	33	0.6	2.2	0.9	1.6	-	
P1-6	274	242	118	20.0	20.4	0.3	-	0.3	2.4	-	-	-	174	18	-	41	0.7	2.4	-	-	-	
P1-8	-	268	90	15.0	20.0	0.1	102.5	1.0	2.8	8.6	0.0	4.6	220	38	-	55	1.4	3.5	3.8	0.9	1.3	
P1-9	289	290	63	14.0	15.2	0.3	195.0	1.3	3.5	9.5	0.1	7.3	212	56	-	50	1.8	3.9	1.9	2.1	1.2	
P1-10	291	270	105	12.7	15.4	0.0	127.5	0.4	3.9	7.5	0.0	5.2	188	40	2.2	56	1.0	2.7	0.4	1.4	1.5	
P1-12	344	250	119	13.0	15.6	1.3	146.0	1.0	1.1	10.5	0.0	4.3	143	60	-	55	1.0	2.3	7.9	0.5	0.7	
P1-14	210	244	101	18.0	18.9	0.2	144.5	2.1	3.6	6.0	0.2	7.7	198	35	-	46	1.7	2.4	2.6	0.9	1.9	
P1-15	274	236	92	16.0	18.3	0.1	257.0	0.7	1.9	4.8	0.2	5.7	196	40	-	43	1.5	2.4	1.7	0.7	1.0	
P1-16	-	250	88	21.0	22.2	0.2	238.0	10.0	11.4	2.3	0.0	14.7	216	58	-	-	10.0	10.3	0.6	0.2	1.2	
P1-19	276	236	80	18.0	18.8	0.1	79.0	1.0	1.7	10.0	0.9	2.8	150	22	-	40	0.1	1.9	6.5	1.4	1.0	
P1-20	282	-	92	16.0	18.8	0.1	25.0	0.0	1.3	9.3	1.1	3.1	--	17	-	36	0.0	1.9	4.6	2.9	-	
P1-21	312	247	86	21.0	22.9	0.0	80.4	0.2	1.5	8.5	2.0	3.4	247	16	-	37	0.5	1.5	4.5	4.0	-	
P1-22	320	248	82	20.0	21.9	0.0	78.7	8.0	9.2	1.3	0.9	10.1	214	30	-	40	7.0	9.1	0.0	0.1	-	
P1-25	289	224	94	16.0	18.6	0.0	154.5	0.2	1.4	10.5	0.0	3.9	140	20	-	42	1.0	1.5	7.2	0.3	-	
P1-26	278	205	75	13.0	18.5	0.0	135	0.2	1.0	11.0	0.0	2.2	132	25	-	39	1.0	1.7	5.0	0.2	-	
P1-27	270	234	70	17.0	20.4	0.4	145	0.6	2.2	14.4	0.0	2.6	134	43	-	30	0.4	2.3	11.5	0.0	-	

Cont'd...../

TABLE B2 (CONT'D). ANALYTICAL RESULTS FOR CONTINUOUS RUNS (ALL VALUES IN  $\text{mg}\cdot\text{L}^{-1}$ )  
SYSTEM A

Run No.	Feed						System	Aerobic Reactor				Effluent									
	Unfiltered		Filtered				Weighted Mean MLSS Unfiltered TKN	Filtered				Unfiltered				Filtered					
	COD	Alk	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N		NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N	NO <sub>2</sub> <sup>-</sup> -N	TKN	Alk	SS	TP	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N	NO <sub>2</sub> <sup>-</sup> -N	TP
P1-34	380	234	122	22.0	23.4	0.2	171	12.0	13.9	2.1	0.0	19.5	204	66	-	40	12.0	14.0	0.0	0.0	-
P1-35	374	190	124	21.0	26.4	0.2	249.5	11.0	14.7	2.3	0.5	21.4	178	93	-	52	13.0	17.2	0.2	0.0	-
P1-39	480	252	150	25.0	28.7	0.2	325.0	11.0	12.4	2.2	0.9	12.7	210	11	3.6	39	9.0	10.7	0.0	0.0	3.0
P1-40	440	198	117	24.0	30.4	0.2	292.5	8.0	11.4	3.7	0.9	13.0	164	13	4.2	46	8.0	11.1	0.0	0.4	3.8
P1-43	-	176	55	11.2	14.5	1.2	182.5	2.3	0.2	8.9	0.1	2.3	118	25	2.2	31	0.1	0.4	5.1	0.8	1.0
P1-44	430	148	162	23.0	24.6	1.6	180.0	7.0	8.4	7.9	0.8	9.6	126	8	2.7	43	7.0	8.1	0.2	0.3	2.3
P1-46	320	144	111	18.1	20.8	0.5	150	4.0	4.2	4.3	0.6	6.1	132	12	1.8	41	5.0	5.2	0.2	0.1	1.3
P2-51	240	224	110	18.0	18.6	3.2	134	0.0	1.1	10.1	0.1	2.9	170	9	2.4	27	1.0	2.0	0.2	0.4	1.7
P2-52	210	205	52	12.0	14.7	2.9	291	1.0	2.1	5.6	0.1	3.0	184	8	1.9	24	0.8	2.0	0.6	0.5	1.2
P2-54	260	224	98	17.0	18.0	0.7	245	0.6	1.6	11.9	0.2	3.5	164	7	2.2	39	1.5	1.8	4.2	1.1	0.6
P2-55	260	240	87	11.0	14.1	0.7	169	0.4	1.7	1.5	0.0	2.8	-	16	2.9	35	0.8	1.5	0.6	0.2	1.8
P2-57	330	230	110	15.0	20.8	0.4	373	0.1	2.3	5.2	0.3	3.9	190	21	2.7	28	1.0	1.8	0.6	0.1	1.6
P2-58	368	259	130	18.0	23.1	0.4	284	0.3	2.2	2.2	0.3	4.5	194	25	3.3	24	0.6	2.6	0.6	0.1	2.1
P2-60	270	245	110	15.0	19.3	0.6	211	0.3	1.4	6.7	0.5	2.5	160	5	2.5	35	0.6	1.5	4.2	1.5	2.1
P2-61	260	233	97	16.0	18.6	0.4	239	2.0	4.2	5.5	0.9	5.6	174	6	1.9	31	0.2	4.9	3.7	1.6	0.9
P2-64	340	238	110	20.0	25.4	2.6	266	5.0	6.3	4.7	0.2	8.8	195	10	2.1	28	5.0	6.5	0.1	0.9	1.0
P2-65	320	228	120	16.0	19.8	0.1	309	2.0	6.4	4.2	0.1	7.6	178	13	1.9	36	2.0	5.7	0.1	0.3	1.0
P2-66	300	268	110	20.0	22.7	0.1	255	-	-	2.5	0.1	4.2	182	9	3.1	39	2.0	2.0	0.0	0.2	1.9
P2-67	300	226	95	18.0	23.4	0.3	269	0.0	1.3	6.8	0.1	4.2	174	14	3.6	36	1.0	2.1	0.4	0.2	2.3
P2-68	340	196	130	19.0	19.8	0.3	212	0.0	1.3	2.7	0.1	3.7	151	9	2.5	31	1.0	1.7	0.0	0.0	1.4
P2-69	300	228	120	16.0	22.6	0.1	-	1.0	2.2	5.6	0.0	4.0	168	3	2.7	24	1.0	2.1	0.2	0.0	1.8

TABLE B2. ANALYTICAL RESULTS FOR CONTINUOUS RUNS (ALL VALUES IN  $\text{mg}\cdot\text{L}^{-1}$ )  
SYSTEM B

Run No.	Feed						System	Aerobic Reactor			Effluent									
	Unfiltered		Filtered				Weighted Mean MLSS Unfiltered TKN	Filtered			Unfiltered				Filtered					
	COD	Alk	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N		NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N	TKN	Alk	SS	TP	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N	TP	
P1-3	-	284	-	17.0	19.9	-	51.7	1.1	2.3	-	2.1	158	43	-	-	0.6	1.6	-	-	
P1-4	-	282	-	16.0	17.9	-	43.0	1.3	2.4	-	3.7	174	44	-	-	0.9	1.4	-	-	
P1-5	310	250	113	18.0	19.5	0.3	98.0	0.6	1.9	7.7	5.2	224	46	-	46	0.5	2.2	0.2	-	
P1-6	274	242	118	20.0	20.4	0.3	64.0	0.4	1.7	7.7	4.4	184	63	-	62	0.6	2.0	0.2	-	
P1-8	-	268	90	15.0	20.0	0.1	43.0	6.0	7.8	2.3	11.4	244	84	-	95	6.0	8.4	0.1	1.0	
P1-9	289	290	63	14.0	15.2	0.3	67.0	7.0	10.2	2.6	18.6	238	88	-	60	6.7	7.3	0.3	0.7	
P1-10	291	270	105	12.7	15.4	0.0	43.5	5.2	8.0	2.0	10.3	196	75	2.6	135	4.1	5.5	0.0	1.2	
P1-12	344	250	119	13.0	15.6	1.3	70.5	1.0	2.9	6.0	7.3	168	75	-	74	1.0	3.7	3.2	0.5	
P1-13	245	230	74	18.0	18.1	0.8	181.5	2.4	3.9	5.9	5.4	200	50	-	76	1.4	3.9	0.4	1.9	
P1-14	210	244	101	18.0	18.9	0.2	165.0	0.5	1.9	5.3	4.2	196	61	-	79	0.5	1.6	0.2	1.2	
P1-15	274	236	92	16.0	18.3	0.1	226.0	1.0	2.8	5.1	4.2	198	62	4.2	90	0.1	1.5	0.8	1.4	
P1-16	246	250	88	21.0	22.2	0.2	242.5	9.0	9.3	2.6	12.6	210	85	-	106	7.6	9.2	0.1	0.6	
P1-17	289	254	97	19.0	20.2	0.6	228.0	10.0	10.3	3.3	16.2	222	67	-	125	9.0	9.6	2.2	1.6	
P1-19	276	236	80	18.0	18.8	0.1	88.6	7.0	9.9	-	12.6	202	54	-	95	6.1	8.8	-	0.7	
P1-20	282	-	92	16.0	18.8	0.1	61.9	0.0	2.3	11.8	3.4	-	43	-	60	0.0	2.2	1.8	-	
P1-21	312	247	86	21.0	22.9	0.0	78.0	1.4	3.4	5.0	4.2	180	50	-	80	1.2	2.6	0.3	-	
P1-22	320	248	82	20.0	21.9	0.0	66.8	6.0	7.7	4.0	8.6	204	57	-	72	5.0	6.3	0.1	-	

Cont'd...../

TABLE B2 (CONT'D). ANALYTICAL RESULTS FOR CONTINUOUS RUNS (ALL VALUES IN  $\text{mg}\cdot\text{L}^{-1}$ )  
SYSTEM B

Run No.	Feed						System	Aerobic Reactor			Effluent									
	Unfiltered		Filtered				Weighted Mean MLSS Unfiltered TKN	Filtered			Unfiltered				Filtered					
	COD	Alk	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N		NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N	TKN	Alk	SS	TP	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N	TP	
P1-23	312	234	78	21.0	24.4	0.2	92.0	1.0	3.4	7.0	7.0	166	52	-	59	1.0	2.9	0.0	-	
P1-24	357	230	111	16.0	19.6	0.2	20.0	0.2	1.3	5.9	3.3	167	45	-	73	1.0	1.0	0.0	-	
P1-25	-	224	-	16.0	18.6	0.0	73.3	0.1	1.4	-	3.5	140	56	-	--	0.2	1.6	-	-	
P1-26	278	205	75	13.0	18.5	0.0	28.1	0.1	0.7	-	2.6	100	57	-	37	1.0	1.1	-	-	
P1-27	-	234	-	17.0	20.4	0.4	53.0	0.2	2.0	-	3.5	156	68	-	--	0.6	2.3	-	-	
P1-28	272	224	75	18.0	20.6	0.0	59.3	0.9	2.0	6.6	4.0	170	88	-	79	1.0	2.4	0.0	-	
P1-29	417	190	133	20.0	26.2	0.0	71.6	14.0	15.5	0.9	28.2	200	148	5.7	101	13.0	14.9	0.0	1.7	
P1-30	380	173	97	20.0	24.4	4.1	73.4	14.0	15.2	2.0	33.2	146	121	6.7	107	14.0	16.7	1.1	2.2	
P1-34	480	234	122	22.0	23.4	0.2	37.1	15.0	17.6	0.3	28.2	210	99	-	112	16.0	18.7	0.0	-	
P1-35	440	190	124	21.0	26.4	0.2	60.0	16.0	21.8	0.5	31.3	179	178	-	96	16.0	22.0	0.1	-	
P1-36	408	269	118	20.0	28.7	0.2	87.5	15.0	16.2	0.3	18.9	266	137	-	109	16.0	16.9	0.0	-	
P1-39	480	252	150	25.0	28.7	0.2	239.5	16.0	16.6	2.0	17.0	230	37	3.6	90	14.0	15.2	0.2	3.3	
P1-41	230	170	92	11.9	14.4	1.0	119.5	2.2	2.5	4.6	3.1	134	28	2.4	70	0.2	2.1	0.3	1.8	
P1-42	240	200	102	13.0	13.4	0.9	230.0	0.9	3.0	5.6	3.9	130	63	1.9	54	0.8	2.1	0.0	1.0	
P1-43	-	176	55	11.2	14.5	1.2	175.0	0.0	0.0	5.6	2.4	133	58	2.7	55	0.1	0.4	0.8	1.7	
P1-44	430	148	162	23.0	24.6	1.6	154.0	8.0	8.3	8.9	11.6	116	62	3.5	48	7.0	8.0	0.6	2.0	
P1-45	380	187	103	20.0	22.7	0.3	114.0	3.0	4.7	6.6	5.3	137	26	3.0	36	3.0	3.9	1.2	2.3	

Cont'd...../



TABLE B2. ANALYTICAL RESULTS FOR CONTINUOUS RUNS (ALL VALUES IN  $\text{mg}\cdot\text{L}^{-1}$ )  
SYSTEM C

Run No.	Feed						System	Anoxic Reactor			Effluent									
	Unfiltered		Filtered				Weighted Mean MLSS Unfiltered TKN	Filtered			Unfiltered				Filtered					
	COD	Alk	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N		NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N	TKN	Alk	SS	TP	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N	TP	
P1-3	293	284	105	17.0	19.9	1.7	57	5.8	16.5	0.2	2.2	208	9	-	33	2.0	2.0	2.4	-	
P1-4	264	282	92	16.0	17.9	0.0	51	5.0	14.9	0.1	2.0	220	9	-	29	0.9	1.5	3.3	-	
P1-5	310	250	113	18.0	19.5	0.3	156	0.1	1.1	0.1	2.2	182	5	-	33	0.6	1.5	0.6	-	
P1-6	274	242	118	20.0	20.4	0.3	127	4.6	6.8	0.0	3.1	198	8	-	56	1.0	2.6	2.0	-	
P1-7	211	270	79	12.0	19.7	0.7	57	1.9	3.9	0.0	2.4	196	30	-	56	1.0	1.1	0.7	-	
P1-9	289	290	63	14.0	15.2	0.3	72	2.7	3.6	0.0	3.2	224	27	-	36	1.1	2.3	0.5	0.1	
P1-10	291	270	105	12.7	15.4	0.0	100	7.3	8.3	0.0	8.4	220	28	2.6	56	3.9	5.5	0.7	-	
P1-11	251	252	95	11.9	13.8	0.4	90	5.4	6.6	0.0	7.1	202	29	1.1	45	3.8	5.5	0.7	0.6	
P1-12	344	250	119	13.0	15.6	1.3	84	4.0	5.0	0.5	6.3	200	10	-	39	2.0	2.5	0.8	0.5	
P1-13	245	230	74	18.0	18.1	0.8	235	4.7	7.7	0.0	4.3	182	14	-	40	1.5	2.2	0.6	0.3	
P1-14	210	244	101	18.0	18.9	0.2	339	6.4	10.9	0.0	4.6	214	5	-	55	2.9	3.7	1.1	0.9	
P1-15	274	236	92	16.0	18.3	0.1	332	9.0	13.3	0.1	6.7	186	5	-	49	4.6	5.4	1.4	0.9	
P1-16	246	250	88	21.0	22.2	0.2	333	12.0	13.0	0.1	11.4	210	5	-	48	9.8	9.8	0.6	-	
P1-17	289	254	97	19.0	20.2	0.6	251	11.9	14.6	0.1	9.8	224	16	-	55	7.8	8.1	0.5	-	
P1-18	254	252	47	16.0	22.0	0.0	47	4.0	5.0	0.1	8.8	210	17	-	48	8.0	8.0	0.0	0.0	
P1-19	276	236	80	18.0	18.8	0.1	74	8.0	12.5	-	10.6	142	16	-	63	7.6	9.9	-	-	
P1-20	282	-	92	16.0	18.8	0.1	90	6.0	7.6	0.0	5.1	-	9	-	45	2.0	4.0	2.2	-	
P1-21	312	247	86	21.0	22.9	0.0	49	6.0	9.0	1.4	6.7	180	11	-	51	4.0	5.2	4.5	-	

Cont'd...../

TABLE B2 (CONT'D). ANALYTICAL RESULTS FOR CONTINUOUS RUNS (ALL VALUES IN  $\text{mg}\cdot\text{L}^{-1}$ )  
SYSTEM C

Run No.	Feed						System	Anoxic Reactor			Effluent								
	Unfiltered		Filtered				Weighted Mean MLSS Unfiltered TKN	Filtered			Unfiltered				Filtered				
	COD	Alk	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N		NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N	TKN	Alk	SS	TP	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N	TP
P1-22	320	248	82	20.0	21.9	0.0	74	10.0	11.3	0.0	8.9	214	11	-	44	6.8	7.9	0.4	-
P1-25	289	224	94	16.0	18.6	0.0	101	0.2	2.3	0.0	2.6	154	14	-	47	0.3	1.7	2.0	-
P1-26	278	205	70	13.0	18.5	0.0	85	2.0	3.2	0.0	2.4	139	13	-	39	1.0	1.4	1.4	-
P1-27	270	234	70	17.0	20.4	0.4	94	3.0	5.6	0.5	2.6	174	8	-	37	0.8	1.9	2.2	-
P1-28	272	224	75	18.0	20.6	0.0	88	3.8	6.1	0.0	2.4	160	10	-	39	0.6	1.8	2.1	-
P1-31	420	228	132	23.0	26.0	0.0	117	15.0	19.0	0.0	18.9	206	43	-	158	11.0	13.3	0.0	-
P1-32	390	190	141	22.0	25.1	0.2	115	18.0	22.0	0.0	20.3	182	34	-	119	9.0	13.9	0.0	-
P1-33	410	238	97	20.0	24.4	1.9	117	14.0	17.9	0.5	15.5	214	69	-	71	10.0	13.0	1.4	-
P1-34	480	234	122	22.0	23.4	0.2	143	16.0	18.3	0.0	27.4	204	35	-	86	11.0	16.2	0.0	-
P1-37	390	242	46	21.0	22.1	0.6	250	13.0	13.7	0.3	10.1	204	10	1.8	47	7.0	7.4	0.3	1.3
P1-38	300	272	49	25.0	26.6	0.2	190	15.0	16.2	0.7	18.7	226	5	2.8	30	13.0	14.2	1.0	2.5
P1-39	480	252	150	25.0	28.7	0.2	287	16.0	16.3	0.4	16.5	216	10	2.8	46	15.0	15.5	1.5	2.3
P1-41	230	170	92	11.9	14.4	1.0	206	2.1	3.5	0.4	2.2	138	7	0.4	33	0.3	1.4	1.4	0.0
P1-42	240	200	102	13.0	13.4	0.9	163	5.9	8.4	0.4	3.6	128	8	0.9	29	0.9	2.8	3.1	0.7
P1-43*	-	176	53	12.2	15.2	1.4	157	2.6	3.1	0.7	1.7	130	12	1.3	27	0.3	0.9	3.5	0.9
P1-44	430	148	162	23.0	24.6	1.6	238	8.9	11.0	0.2	7.6	130	6	1.6	48	5.0	6.6	2.8	1.5
P1-45	380	187	103	20.0	22.7	0.3	199	7.0	7.2	0.4	4.2	136	5	1.3	38	2.0	3.2	2.6	1.1
P1-46	320	144	111	18.1	20.8	0.5	248	4.8	5.9	0.2	2.3	106	4	0.9	46	1.3	2.3	2.8	0.8

\* System C feed sampled separately from systems A and B for Run P1-43.

Cont'd...../

TABLE B2 (CONT'D). ANALYTICAL RESULTS FOR CONTINUOUS RUNS (ALL VALUES IN  $\text{mg}\cdot\text{L}^{-1}$ )  
SYSTEM C

Run No.	Feed						System	Anoxic Reactor			Effluent									
	Unfiltered		Filtered				Weighted Mean MLSS Unfiltered TKN	Filtered			Unfiltered				Filtered					
	COD	Alk	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N		NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N	TKN	Alk	SS	TP	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N	TP	
P2-52	210	205	52	12.0	14.7	2.9	173	2.0	3.7	1.9	1.9	186	12	0.8	24	0.2	1.0	6.4	0.4	
P2-53	230	220	87	13.0	19.4	1.0	-	3.0	4.6	0.1	3.5	172	13	1.9	35	0.2	2.3	3.7	1.3	
P2-55	260	240	87	11.0	14.1	0.7	-	2.0	3.2	0.2	2.1	192	7	1.6	43	0.2	1.0	2.1	0.7	
P2-56	250	248	87	15.0	19.6	0.7	-	3.0	6.3	0.9	5.1	196	20	2.3	28	0.6	2.9	3.2	1.0	
P2-59	430	249	130	17.0	24.0	0.1	-	3.0	6.9	0.1	3.0	183	10	2.6	24	0.3	1.8	3.0	1.9	

Cont'd...../

TABLE B2. ANALYTICAL RESULTS FOR CONTINUOUS RUNS (ALL VALUES IN  $\text{mg}\cdot\text{L}^{-1}$ )  
SYSTEM D

Run No.	Feed						System	Anoxic Reactor			Effluent									
	Unfiltered		Filtered				Weighted Mean MLSS Unfiltered TKN	Filtered			Unfiltered				Filtered					
	COD	Alk	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N		NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N	TKN	Alk	SS	TP	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N	T	
P1-1	298	226	106	13.5	18.7	0.2	+200	4.0	11.2	6.1	3.9	170	8	-	49	2.0	3.1	11.4	-	
P1-2	306	250	110	16.0	16.4	0.5	147.5	2.6	12.3	3.5	4.3	170	8	-	-	3.0	4.0	9.6	-	
P2-47	230	176	119	16.3	17.1	1.3	185	4.9	5.5	3.0	1.5	114	3	1.9	41	0.8	1.2	7.3	1.9	
P2-48	280	178	130	18.0	21.4	0.9	195	6.0	6.7	2.4	4.4	120	5	3.1	32	3.0	3.5	7.4	2.9	
P2-49	260	186	110	17.0	18.8	0.9	243	5.0	5.3	2.8	2.3	110	5	2.5	28	2.0	2.2	8.2	2.4	
P2-50	240	230	120	15.0	17.1	1.7	-	3.0	4.4	7.8	1.4	142	10	1.8	39	0.2	0.6	15.1	1.4	
P2-51	220	224	110	18.0	18.6	3.2	-	2.0	3.8	8.8	1.2	146	8	1.8	31	0.2	0.3	18.5	1.0	
P2-57	330	230	110	15.0	20.8	0.4	-	0.1	0.9	4.9	5.5	154	22	2.6	36	0.1	1.7	8.4	1.4	
P2-58	368	259	130	18.0	23.1	0.4	-	3.0	6.0	2.9	3.8	168	18	2.9	36	1.0	3.2	6.2	2.1	
P2-62	300	214	91	20.0	21.0	0.2	130	6.0	11.8	0.2	6.7	167	3	1.1	34	4.0	4.4	0.7	0.8	
P2-63	350	250	91	18.0	21.4	0.4	181	8.0	9.2	0.1	14.4	206	1	1.0	27	6.0	8.4	0.6	0.3	
P2-65*	320 (27.9)	228	120	16.0	19.8	0.1	223	4.0	6.8	0.4	3.3	174	1	1.0	36	2.0	2.0	1.2	0.3	
P2-66	300	268	110	20.0	22.7	0.1	189	4.0	5.8	-	11.3	204	2	1.5	27	-	-	1.4	0.6	
P2-67*	300 (33.1)	226	95	18.0	23.4	0.3	233	5.0	8.5	0.3	6.2	165	5	3.6	28	1.0	4.7	3.4	2.8	
P2-68*	340 (26.8)	196	130	19.0	19.8	0.3	-	5.0	5.0	0.4	3.2	139	6	2.7	31	1.0	1.7	2.1	1.5	
P2-69*	300 (31.7)	228	120	16.0	22.6	0.1	-	4.0	7.3	0.5	2.1	154	6	1.9	24	1.0	1.7	3.6	1.6	

\* Values in brackets are unfiltered TKN results.

† Based on composite value for C1 only.

Cont'd...../

TABLE B2. ANALYTICAL RESULTS FOR CONTINUOUS RUNS (ALL VALUES IN  $\text{mg}\cdot\text{L}^{-1}$ )  
SYSTEM E

Run No.	Feed					System	Effluent								
	Unfiltered	Filtered				Weighted Mean MLSS Unfiltered TKN	Unfiltered			Filtered					
	COD	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N +NO <sub>2</sub> <sup>-</sup> -N		TKN	SS	TP	COD	NH <sub>3</sub> -N	TKN	NO <sub>3</sub> <sup>-</sup> -N	TP	
P2-51	220	110	18.0	18.6	3.2	102	1.4	9	1.9	31	0.0	0.6	13.6	1.6	
P2-52	210	52	12.0	14.7	2.9	214	2.4	12	1.2	28	0.2	1.3	11.8	0.8	
P2-53	230	87	13.0	19.4	1.0	174	3.2	20	2.7	32	1.0	1.5	11.7	1.5	
P2-54	260	98	17.0	18.0	0.7	-	2.1	24	1.9	43	0.5	1.6	9.7	1.3	
P2-55	260	87	11.0	14.1	0.7	-	2.4	30	1.8	31	0.4	1.7	9.7	1.0	
P2-56	250	87	15.0	19.6	0.7	180	4.0	32	2.8	32	0.7	2.8	12.0	1.8	
P2-57	330	110	15.0	20.8	0.4	--	3.1	30	2.3	36	0.1	2.4	10.9	1.5	
P2-58	368	130	18.0	23.1	0.4	205	3.7	33	2.7	36	0.1	3.2	9.9	2.1	
P2-60	270	110	15.0	19.3	0.6	374	3.3	28	3.1	31	0.8	2.8	10.4	2.0	
P2-61	260	97	16.0	18.6	0.4	396	2.4	27	1.7	31	0.0	2.2	10.9	0.7	
P2-63*	350	91	18.0	21.4	0.4	254	1.8	12	1.7	45	1.0	1.0	7.9	1.2	
P2-64*	340	140	20.0	25.4	2.6	356	-	4	2.7	31	1.0	1.6	10.1	0.5	
P2-66*	360	180	20.0	21.1	0.1	268	1.8	4	1.8	31	1.0	1.6	2.2	1.3	
P2-67*	350	150	17.0	23.6	0.3	319	1.7	4	2.0	28	1.0	1.0	4.0	1.5	
P2-68*	390	190	18.0	19.0	0.0	-	1.4	11	1.4	35	1.0	1.0	1.9	1.4	

\* Feed for system E sampled separately and includes CH<sub>3</sub>OH added.

TABLE B3. PILOT PLANT BATCH NITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Aerobic SRT ( $\theta_1$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g Filtered TKN}}{\text{g MLVSS} \cdot \text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
09/7/76	A1	12.0	4.8	0.0	14.5	2 560	43	8.0	12.2	0.1	6.8	0.037 4
				0.5			42	7.0	10.5	0.1	9.1	
				1.0			42	7.0	8.1	0.1	16.1	
				1.5			39	4.0	5.4	0.1	15.6	
				2.0			39	1.0	3.5	0.0	12.7	
				2.5			39	1.0	1.8	0.1	17.1	
				3.0			31	1.0	1.1	0.1	14.5	
13/8/76	A1	21.0	8.4	0.0	7.5	3 270	46	14.0	15.3	0.5	7.9	0.019 8
				0.5			42	13.0	14.4	0.2	8.6	
				1.0			42	11.0	12.8	0.1	10.6	
				1.5			43	10.0	11.1	0.1	10.6	
				2.0			42	9.0	10.2	0.2	13.0	
				2.5			42	7.0	9.0	0.2	14.5	
				3.0			39	6.0	7.1	0.2	16.3	

Cont'd...../

TABLE B3 (CONT'D). PILOT PLANT BATCH NITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Aerobic SRT ( $\theta_1$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate g Filtered TKN g MLVSS•day
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
09/9/76	A1	7.0	2.8	0.0	14.5	2 030	40	10.0	12.3	0.5	12.0	0.045 7
				0.5			39	8.0	9.5	0.8	14.4	
				1.0			36	5.0	7.3	0.7	14.0	
				1.5			38	2.0	4.8	0.7	13.8	
				2.0			38	0.0	2.3	1.1	21.3	
				2.5			38	0.0	1.0	0.4	22.8	
22/9/76	A1	3.0	1.2	0.0	25.0	920	41	9.5	11.6	1.5	5.6	
				0.5			39	6.8	8.5	2.3	7.0	
				1.0			42	3.7	5.1	3.2	8.7	
				1.5			38	1.2	2.5	2.5	11.5	
				2.0			37	0.0	1.4	3.8	9.7	
				2.5			36	0.0	1.4	0.5	13.3	
				3.0			37	0.0	1.5	0.1	13.7	
				4.0	23.0		37	0.0	1.6	0.1	13.7	0.078 6

Cont'd...../

TABLE B3 (CONT'D). PILOT PLANT BATCH NITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Aerobic SRT ( $\theta_1$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g Filtered TKN}}{\text{g MLVSS} \cdot \text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> -N	NO <sub>3</sub> -N	
22/10/76	A1	16	6.4	0.0	25.0	3 390	41	7.0	8.3	0.2	13.3	0.055 7
				0.5			37	1.8	3.8	0.5	18.5	
				1.0			30	0.3	0.7	0.0	19.3	
				1.5			34	0.1	0.5	0.0	22.0	
				2.0			34	0.1	0.3	0.0	23.3	
				2.5			34	0.2	0.4	0.0	22.8	
				3.0	23.0	3 160	37	0.1	0.2	0.0	22.7	
04/12/76	A1	10	4.0	0.0	5.0	3 230	23	27.6	28.0	0.8	3.2	
				0.5			41	30.0	31.3	1.3	5.0	
				1.5			41	26.0	27.7	1.2	5.2	
				2.5			42	28.0	28.4	2.3	8.8	
				3.0			41	25.0	26.2	2.0	8.8	
				4.0			42	25.0	26.0	2.8	12.4	
				5.0			46	16.0	16.8	2.9	12.9	
				6.0	6.5	3 130	48	18.0	18.8	3.0	13.0	
				7.0			45	14.0	14.5	4.4	18.2	
												0.016 7

Cont'd...../



TABLE B3 (CONT'D). PILOT PLANT BATCH NITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Aerobic SRT ( $\theta_1$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate g Filtered TKN g MLVSS·day
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> -N	NO <sub>3</sub> -N	
07/1/77	A1	30	12	0.0	8.0	4 900	56	21.0	23.5	1.5	5.8	
				0.5			43	20.0	21.9	2.1	7.5	
				1.0			46	19.0	20.9	2.6	9.3	
				1.5			48	19.0	19.7	3.3	10.4	
				2.0			48	18.0	18.6	3.7	10.6	
				2.5			44	18.0	18.0	4.7	11.2	
				3.0			43	15.0	16.5	4.7	13.5	
				4.0			49	11.0	14.8	5.2	14.1	
				5.0			46	9.0	9.5	6.3	15.7	
				6.0			44	6.0	7.3	6.3	15.8	
13/8/76	B1	10	7.1	7.0	8.5	5 010	51	4.0	5.3	6.8	16.0	0.012 8
				0.0			50	9.0	9.9	0.3	5.3	
				0.5			50	8.0	9.1	0.3	6.0	
				1.0			44	7.0	8.1	0.4	7.5	
				1.5			45	7.0	7.6	0.5	10.6	
				2.0			46	4.0	5.0	0.3	7.1	
				2.5			47	3.0	4.2	0.4	8.7	
				3.0			45	2.0	2.8	0.5	10.7	
				4.0			45	1.0	1.8	0.1	11.4	
				5.0			44	0.6	1.0	0.0	14.0	
					9.0	2 390						0.022 7

Cont'd...../

TABLE B3 (CONT'D). PILOT PLANT BATCH NITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Aerobic SRT ( $\theta_1$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate g Filtered TKN g MLVSS•day
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
09/9/76	B1	2.0	0.6	0.0	15.0	1 030	49	18.0	21.6	0.8	3.0	0.0370
				0.5			46	18.0	18.6	0.9	3.4	
				1.0			48	17.0	19.1	1.0	3.9	
				1.5			49	17.0	17.7	1.0	4.6	
				2.0			49	16.0	17.3	1.1	5.2	
				2.5			48	15.0	16.4	1.2	5.7	
				3.0			48	15.0	15.9	1.3	6.4	
					15.0	1 130						
22/9/76	B1	1.5	0.44	0.0	25.0	720	43	13.0	13.1	3.5	10.0	
				0.5			43	10.0	11.0	2.9	17.5	
				1.0			36	11.0	11.0	7.1	17.8	
				1.5			42	10.0	10.3	6.8	17.0	
				2.0			45	7.0	7.1	6.3	16.0	
				2.5			45	7.0	7.1	11.0	15.2	
				3.0			45	4.0	4.8	9.4	16.2	
				4.0	23.0	970	47	1.6	1.8	11.8	18.4	
												0.078 6

Cont'd...../

TABLE B3 (CONT'D). PILOT PLANT BATCH NITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Aerobic SRT ( $\theta_1$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate g Filtered TKN g MLVSS•day
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> -N	NO <sub>3</sub> -N	
13/10/76	B1	2.5	0.7	0.0	26.5	1 000	41	9.0	10.1	3.1	3.7	0.073 3
				0.5			45	7.0	8.2	4.8	3.9	
				1.0			46	5.0	6.1	6.3	4.5	
				1.5			48	4.0	5.3	7.5	5.2	
				2.0			50	2.0	2.8	9.0	6.0	
				2.5			48	1.0	1.8	9.9	6.3	
				3.0			50	1.0	1.8	9.4	7.8	
				4.0			48	1.0	1.5	7.2	9.9	
22/10/76	B1	5.0	1.4	0.0	25.5	1 720	39	9.0	9.7	1.1	14.0	
				0.5			38	5.0	6.8	2.5	16.1	
				1.0			38	2.0	3.0	3.8	18.3	
				1.5			39	1.0	1.9	4.6	19.9	
				2.0			41	0.3	0.8	1.9	22.4	
				2.5			37	0.1	0.6	0.0	23.9	
				3.0			36	0.0	0.3	0.0	25.4	
					23.5	1 820						0.061 6

Cont'd...../

TABLE B3 (CONT'D). PILOT PLANT BATCH NITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Aerobic SRT ( $\theta_1$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g Filtered TKN}}{\text{g MLVSS} \cdot \text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
04/12/76	B1	3.0	0.9	0.0	4.5	1 850	55	41.0	41.7	0.0	1.0	0.012 0
				0.5			50	34.0	34.5	0.0	1.0	
				1.5			55	32.0	33.4	0.0	1.0	
				2.0			58	28.0	29.6	0.0	2.0	
				3.0			58	29.0	30.1	0.0	2.0	
				4.0			58	32.0	33.3	0.0	2.0	
				5.0			55	34.0	34.5	0.0	1.6	
				6.0			57	31.0	32.0	0.0	2.3	
				7.0			56	28.0	29.3	0.0	2.1	
05/1/77	B1	14.0	9.9	0.0	7.0	3 620	49	37.0	37.0	0.9	3.2	
				0.5			49	33.0	36.2	1.0	3.4	
				1.0			46	33.0	36.4	1.2	4.0	
				1.5			46	33.0	36.3	1.5	4.5	
				2.0			48	32.0	32.9	1.7	4.7	
				3.0			46	26.0	32.3	1.7	4.7	
				4.0			48	20.0	22.5	1.7	4.9	
				5.3			49	19.0	21.7	2.1	5.2	
				6.0			89	18.0	20.4	2.3	5.6	
				7.0	7.5	3 590	55	18.0	20.2	2.7	5.9	0.019 3

Cont'd...../

TABLE B3 (CONT'D). PILOT PLANT BATCH NITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Aerobic SRT ( $\theta_1$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g Filtered TKN}}{\text{g MLVSS} \cdot \text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
11/7/76	C2	3.0	2.1	0.0	16.0	1 600	45	19.0	20.2	0.8	0.7	0.018 1
				0.5			45	20.0	21.8	1.0	0.8	
				1.0			48	20.0	20.3	1.2	0.9	
				1.5			48	19.0	19.3	1.9	1.4	
				2.0			48	18.0	18.5	2.2	1.5	
				2.5			47	18.0	19.1	2.3	1.4	
				3.0		1 400	48	18.0	18.7	2.7	1.6	
21/7/76	C2	3.5	2.5	0.0	16.0	2 050	51	15.0	18.4	1.3	0.7	0.024 4
				0.5			69	13.0	14.6	4.9	2.1	
				1.0			66	11.0	13.9	4.8	1.7	
				1.5			67	10.0	12.0	5.3	1.7	
				2.0			92	6.0	6.8	3.7	1.2	
				2.5			63	8.0	8.3	0.0	2.4	
				3.0			76	9.0	11.8	8.4	2.1	
				4.0			73	10.0	11.6	13.4	3.3	
				5.0		1 910	92	4.0	5.1	7.0	1.6	

Cont'd...../

TABLE B3 (CONT'D). PILOT PLANT BATCH NITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Aerobic SRT ( $\theta_1$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate g Filtered TKN g MLVSS·day
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
13/8/76	C2	11.0	7.8	0.0	8.5	5 170	58	16.0	16.4	0.0	0.1	0.006 2
				0.5			57	15.0	15.7	1.8	0.9	
				1.0			57	15.0	15.5	2.4	1.3	
				1.5			55	12.0	13.6	2.9	1.6	
				2.0			55	11.0	13.8	3.3	2.1	
				2.5			53	10.0	12.8	3.5	2.2	
				3.0			57	9.0	11.6	3.6	1.9	
				4.0			50	9.0	11.7	3.6	2.3	
09/9/76	C2	1.0	0.7	0.0	15.0	1 000	52	18.0	21.7	0.4	0.5	
				0.5			50	19.0	21.4	0.0	0.0	
				1.0			51	20.0	20.8	0.0	0.0	
				1.5			52	23.0	23.6	0.0	0.2	
				2.0			51	22.0	22.7	0.0	0.2	
				2.5			52	18.0	21.6	0.0	0.1	
				3.0			51	17.0	21.8	0.0	0.2	
				4.0			55	19.0	21.0	0.1	0.3	
					14.5							0.023 5

Cont'd...../

TABLE B3 (CONT'D). PILOT PLANT BATCH NITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Aerobic SRT ( $\theta_1$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g Filtered TKN}}{\text{g MLVSS} \cdot \text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
22/9/76	C2	2.0	1.4	0.0	24.0	862	45	12.0	12.9	2.7	2.1	0.017 6
				0.5			47	11.0	12.6	3.7	2.7	
				1.0			49	11.0	12.5	4.6	3.5	
				1.5			47	10.0	12.1	6.3	5.0	
				2.0			40	9.0	11.5	5.9	5.0	
				2.5			49	9.0	11.0	6.3	5.0	
				3.0			53	9.0	10.3	5.7	4.3	
				4.0			52	9.0	9.9	8.7	7.0	
				5.0			53	9.0	9.4	10.8	8.9	
				6.0			57	9.0	9.2	11.9	9.9	
				7.0			57	8.0	8.5	12.1	10.2	
				7.75			58	8.0	8.3	14.0	11.9	
				8.92	22.0		59	6.0	7.0	13.0	10.7	
22/10/76	C2	4.0	2.8	0.0	24.0	1 680	36	10.0	10.6	0.4	1.8	0.035 6
				0.5			35	9.0	10.2	1.0	2.7	
				1.0			37	7.0	8.3	1.7	4.1	
				1.5			37	6.0	6.6	2.3	5.3	
				2.0			38	4.0	5.5	3.0	6.5	
				2.5			41	3.0	3.7	3.6	7.6	
				3.0			39	2.0	3.1	4.1	8.6	
				4.0			37	0.0	0.8	4.8	11.1	
				5.0	21.5	1 820	38	0.0	0.8	4.8	13.9	

TABLE B3 (CONT'D). PILOT PLANT BATCH NITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Aerobic SRT ( $\theta_1$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g Filtered TKN}}{\text{g MLVSS} \cdot \text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
26/11/76	C2	3.0	2.1	0.0	8.0	2 050	76	24.0	24.2	0.0	0.2	
				0.5			77	23.0	23.2	0.0	0.1	
				1.0			76	21.0	21.6	0.0	0.1	
				1.5			75	20.0	21.0	0.0	0.1	
				2.0			73	20.0	20.6	0.1	0.0	
				2.5			78	20.0	20.5	0.1	0.0	
				3.0			79	20.0	21.1	0.0	0.0	
				4.0			81	20.0	20.9	0.1	0.0	
				5.0			81	19.0	19.4	0.1	0.0	
				6.0			83	16.0	17.4	0.0	0.0	
				7.0	8.5	2 110	84	16.0	17.4	0.1	0.1	
0.009 7												



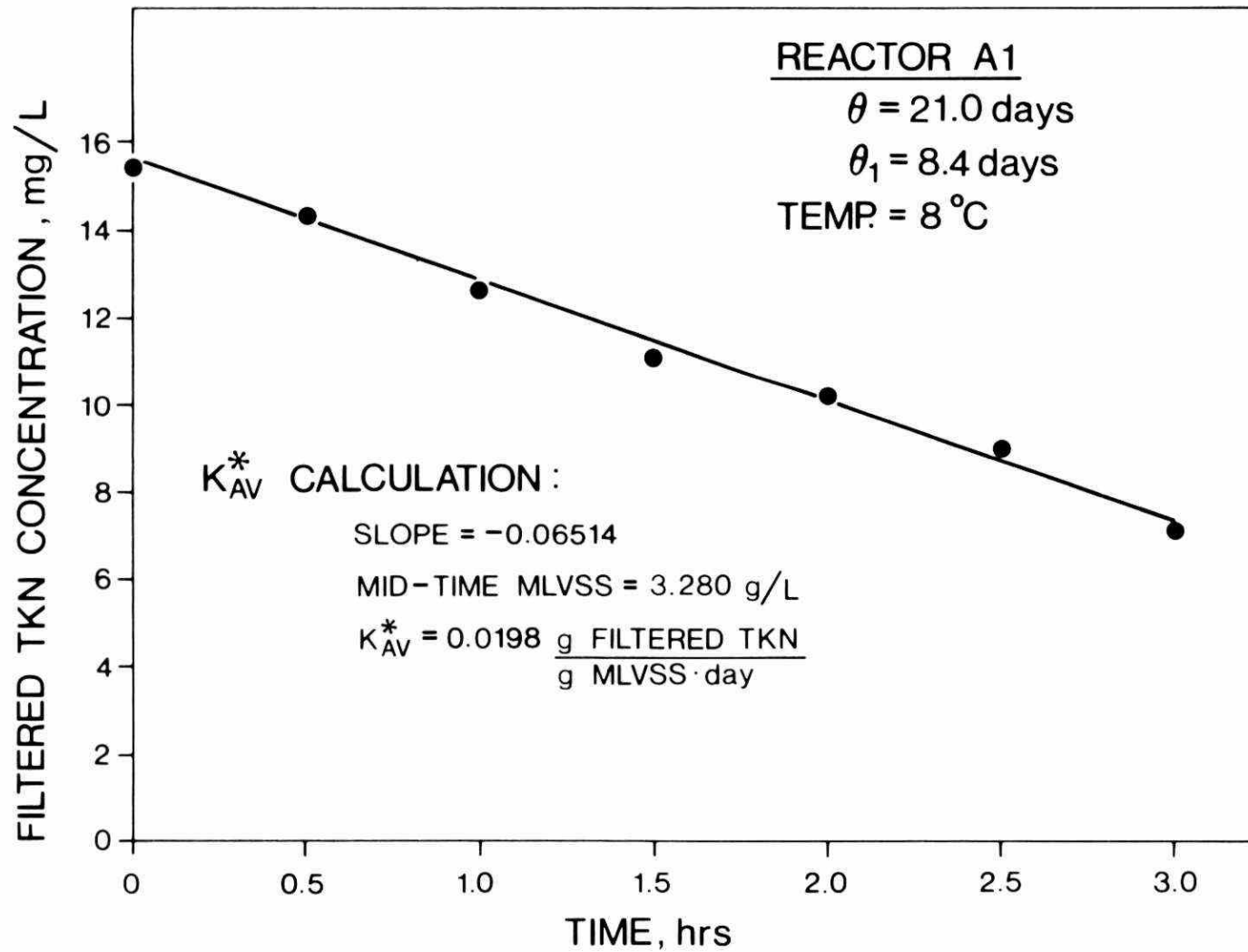


FIGURE B1. NITRIFICATION BATCH TEST

The rates that were then used to determine  $K_A^*$  were rates derived at aerobic SRT's within 0.5 days of  $\theta_{1c}$  (Table B4). To determine  $K_A^*$ , equations 12 and 13 were used. In equation 13, the value for So-S was computed from:

$$\text{So-S} = \text{mean influent COD (Table 1)} + \text{methanol added as COD} - \text{mean effluent filterable COD during Phase I}$$

For system A:

$$\text{So-S} = 325 + 0 - 41 = 284 \text{ mg} \cdot \text{L}^{-1}$$

For system B:

$$\text{So-S} = 325 + 155 - 79.4 = 401 \text{ mg} \cdot \text{L}^{-1}$$

For system C:

$$\text{So-S} = 325 + 280 - 50.6 = 554 \text{ mg} \cdot \text{L}^{-1}$$

The value for  $Y_H$  was taken as  $0.50 \text{ mg} \cdot \text{mg}^{-1}$ .

The value of Ao-A was computed from:

$$\begin{aligned} \text{Ao-A} &= \text{mean influent filterable TKN (Table 1)} \\ &\quad - \text{mean residual filterable TKN (Figure 11)} \\ &= 20.6 - 1.2 = 19.4 \text{ mg} \cdot \text{L}^{-1} \end{aligned}$$

The value of  $Y_{NS}$  was taken as  $0.15 \text{ mg} \cdot \text{mg}^{-1}$  which is the yield coefficient used in completing the overall mass balance (equation 1) as proposed by Haug and McCarty (1972).

A summary of the results and calculations leading to the determination of the  $K_A^*$  values appears in Table B4.

TABLE B4. MAXIMUM AMMONIA OXIDATION RATE RESULTS AND CALCULATIONS

Reactor	Mean Batch Temp. °C	Aerobic SRT ( $\theta_1$ ) days	System SRT ( $\theta$ ) days	$K_{AV}^*$ $g \cdot g^{-1} \cdot day^{-1}$	$\frac{1}{1+0.2b\theta}$	$\frac{Y_{NS}(A_o-A)}{Y_{NS}(A_o-A)+Y_H(S_o-S)}$	$K_A^*$ $g \cdot g^{-1} \cdot day^{-1}$
C2	9.0	7.8	11	0.006 2	0.86	0.010	0.720
B1	8.0	7.1	10	0.022 7	0.91	0.014	1.786
B1	7.5	9.9	14	0.019 3	0.84	0.014	1.643
A1	8.0	8.4	21	0.019 8	0.77	0.020	1.280
A1	8.0	12.0	30	0.012 8	0.93	0.020	0.690
A1	15.0	4.8	12	0.037 4	0.83	0.020	2.255
A1	15.0	2.8	7	0.045 7	0.89	0.020	2.560
C2	24.0	1.4	2	0.017 6	0.96	0.010	1.830
C2	23.0	2.8	4	0.035 6	0.92	0.010	3.870
B1	23.0	1.4	5	0.061 6	0.90	0.014	4.886
A1	24.0	6.4	16	0.055 7	0.74	0.020	3.765

### Pilot Plant Denitrification Batch Experiments

These experiments were carried out in the pilot plant anoxic reactors (A2, B2 and C1) immediately following completion of certain continuous runs. Nitrate in the form of  $\text{NaNO}_3$  was added to each reactor to increase the  $\text{NO}_3\text{-N}$  concentration to a value greater than or equal to 10 mg/L N. Methanol was added to reactor B2 to ensure a minimum initial organic carbon to  $\text{NO}_3\text{-N}$  ratio of 1.2:1. Methanol and influent wastewater were added to reactor C1 to ensure a minimum initial organic carbon to  $\text{NO}_3\text{-N}$  ratio of 1.2:1. The methanol to influent wastewater mixture was maintained equal to that of the Phase 1 continuous runs (not including run P1-38, Table B1) based on the wastewater COD results according to Table 1.

The batch tests began after 10 minutes had elapsed to ensure sufficient mixing of the added components. The results of the experiments appear in Table B5.

### Calculation of Denitrification Rates from Pilot Plant Batch Denitrification Results

The denitrification rates for reactors B2 and C1 were calculated on the basis of the  $\text{NO}_3\text{-N}$  plus  $\text{NO}_2\text{-N}$  results using a similar procedure to that used in determining  $K_{AV}^*$  (Figure B1).  $\text{NO}_3\text{-N}$  plus  $\text{NO}_2\text{-N}$  results were used as normally little or no  $\text{NO}_2\text{-N}$  buildup occurred. In determining the denitrification rates for reactor A2, significant nitrite buildup during certain experiments did not allow the rates to be expressed in terms of  $\text{NO}_3\text{-N}$  plus  $\text{NO}_2\text{-N}$ . A procedure detailed by Stern and Marais (1974) was adopted to determine the equivalent nitrate reduction during the batch experiments when nitrite buildup occurred. The procedure essentially involves correcting the apparent nitrate reduction rate, calculated using  $\text{NO}_3\text{-N}$  results only, by subtracting from this rate the rate of nitrite production on an equivalent nitrate -N basis. This correction is required, as in this case part of the nitrate reduced does not go directly to  $\text{N}_2$  but appears as  $\text{NO}_2\text{-N}$ .

TABLE B5. PILOT PLANT BATCH DENITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Anoxic SRT ( $\theta_2$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g NO}_3\text{-N}}{\text{g MLVSS}\cdot\text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> -N	NO <sub>3</sub> -N	
13/8/76	A2	21.0	12.6	0.0	7.0	3 300	45	6.0	7.7	0.9	17.9	0.010
				0.5			49	7.0	8.1	1.5	17.7	
				1.0			43	7.0	7.9	2.0	17.0	
				1.5			44	6.0	7.4	2.1	13.2	
				2.0			44	6.0	7.2	2.7	12.1	
				2.5			45	5.0	6.1	2.7	9.7	
				3.0			44	5.0	5.8	3.1	8.6	
				4.0			50	7.0	8.0	4.5	8.0	
				5.0			49	8.0	9.3	6.8	6.8	
				6.0	8.0	3 220	47	7.0	8.0	6.7	4.1	
22/9/76	A2	3.0	1.8	0.0	24.5	980	37	0.8	2.0	1.9	11.1	0.034 9
				0.5			34	1.1	2.3	2.1	10.1	
				1.0			36	1.4	2.7	2.4	8.6	
				1.5			37	1.5	2.8	2.6	8.0	
				2.0			38	1.6	3.3	2.8	7.0	
				2.5			38	1.6	3.2	2.9	6.8	
				3.0			35	1.8	3.4	3.0	4.9	
				4.0			36	1.5	2.7	3.2	3.6	
				5.0			36	1.8	2.7	3.3	2.1	
				6.25	23.5	970	36	2.9	3.1	3.0	0.5	

Cont'd...../

TABLE B5 (CONT'D). PILOT PLANT BATCH DENITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Anoxic SRT ( $\theta_2$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g NO}_3\text{-N}}{\text{g MLVSS}\cdot\text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> -N	NO <sub>3</sub> -N	
22/10/76	A2	16.0	9.6	0.0	25.5	3 340	36	1.0	1.9	0.1	16.7	0.012 1
				0.5			34	1.0	1.9	0.1	15.7	
				1.0			34	1.0	2.1	0.1	14.6	
				1.5			36	1.0	1.8	0.2	13.9	
				2.0			37	1.0	1.9	0.1	13.2	
				2.5			36	1.0	1.9	0.1	11.7	
				3.0			33	1.0	1.9	0.1	11.3	
				4.0			37	2.0	2.8	0.1	9.7	
				5.0			36	2.0	3.1	0.1	8.4	
				6.0		3 020	38	2.0	3.0	0.1	7.1	
04/12/76	A2	10.0	6.0	0.0	6.0	3 180	43	16.0	17.1	0.3	18.5	0.023 4
				0.5			39	14.0	15.0	0.3	13.8	
				1.5			41	18.0	18.5	0.5	13.1	
				2.5			40	20.4	21.4	0.3	13.0	
				3.0			40	24.0	25.5	0.6	12.0	
				4.0			40	26.0	28.5	0.2	5.1	
				5.0			40	24.0	25.0	0.0	0.5	
				6.0			42	29.0	29.5	0.0	0.0	
				7.0	7.0	3 250	45	20.0	22.1	0.0	0.0	

Cont'd...../

TABLE B5 (CONT'D). PILOT PLANT BATCH DENITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Anoxic SRT ( $\theta_2$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g NO}_3\text{-N}}{\text{g MLVSS}\cdot\text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
07/1/77	A2	30.0	18.0	0.0	8.5	5 160	44	10.0	11.9	0.9	10.7	
				0.5			49	13.0	13.2	1.6	10.9	
				1.0			43	8.0	12.8	2.2	9.0	
				1.5			44	9.0	12.0	3.2	9.0	
				2.0			44	9.0	12.6	2.4	3.2	
				2.5			39	9.0	12.6	2.3	3.2	
				3.0			44	8.0	13.3	0.9	0.1	
				4.0			41	8.0	12.1	0.9	0.0	
				5.0			43	10.0	12.2	0.0	0.0	
				6.0			43	10.0	12.6	0.0	0.0	
				7.0	9.0	5 070	37	10.0	12.3	0.0	0.0	
0.015 1												
09/7/76	B2	3.0	0.9	0.0	15.0	1 280	94	3.0	5.1	0.2	13.4	
				0.5			99	3.0	5.0	0.1	12.1	
				1.0			79	2.0	5.1	0.1	7.0	
				1.5			78	2.0	4.9	0.1	6.5	
				2.0			70	3.0	5.2	0.1	8.5	
				2.5			57	3.0	5.0	0.1	5.1	
				3.0	15.5	1 040	60	3.0	4.3	0.1	3.9	
0.061 0												

Cont'd...../

TABLE B5 (CONT'D). PILOT PLANT BATCH DENITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Anoxic SRT ( $\theta_2$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g NO}_3\text{-N}}{\text{g MLVSS}\cdot\text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
13/8/76	B2	10.0	2.9	0.0	8.0	3 130	154	0.1	0.6	0.0	8.4	0.024 9
				0.5			147	0.2	0.8	0.0	5.9	
				1.0			139	0.2	0.6	0.0	4.4	
				1.5			125	0.4	1.0	0.0	4.9	
				2.0			121	0.6	1.0	0.0	1.6	
				2.5			116	0.3	0.5	0.0	0.1	
				3.0			109	0.8	1.3	0.0	0.0	
				4.0			115	0.6	1.1	0.0	0.1	
				5.0	9.0	2 860	106	0.6	1.2	0.1	0.0	
09/9/76	B2	2.0	0.6	0.0	15.0	1 090	130	7.0	8.0	0.2	11.6	0.087 8
				0.5			146	6.0	8.1	0.3	9.8	
				1.0			145	6.0	8.2	0.5	7.7	
				1.5			122	6.0	7.5	0.7	5.3	
				2.0			125	6.0	7.6	0.8	2.9	
				2.5			121	6.0	7.3	1.1	1.0	
				3.0	15.5	1 070	120	6.0	6.8	0.2	0.0	

Cont'd...../



TABLE B5 (CONT'D). PILOT PLANT BATCH DENITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Anoxic SRT ( $\theta_2$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g NO}_3\text{-N}}{\text{g MLVSS}\cdot\text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
22/9/76	B2	1.5	0.44	0.0	24.5	700	126	1.7	2.1	1.5	10.3	0.203 0
				0.5			110	1.7	2.1	2.3	6.9	
				1.0			95	1.1	2.0	3.5	2.3	
				1.5			87	1.2	2.0	3.2	0.0	
				2.0			84	0.4	2.3	0.0	0.0	
				2.5			75	0.6	1.8	0.0	0.0	
				3.0			71	0.8	1.9	0.0	0.0	
				4.0			77	1.3	2.2	0.0	0.0	
13/10/76	B2	2.5	0.7	0.0	26.5	1 040	116	0.0	0.2	0.5	9.3	0.149 5
				0.5			104	0.0	0.1	0.5	5.4	
				1.0			87	0.0	0.0	0.5	2.1	
				1.5			80	0.0	0.2	0.0	0.0	
				2.0			77	0.0	0.1	0.0	0.0	
				2.5			78	0.0	0.3	0.0	0.0	
				3.0			74	0.0	0.2	0.0	0.0	
				4.0			69	0.0	0.2	0.0	0.0	

Cont'd...../

TABLE B5 (CONT'D). PILOT PLANT BATCH DENITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Anoxic SRT ( $\theta_2$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g NO}_3\text{-N}}{\text{g MLVSS}\cdot\text{day}}$	
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N		
04/12/76	B2	3.0	0.9	0.0	5.0	1 830	192	19.0	19.6	0.0	19.7	0.032 4	
				0.5			188	17.0	17.5	0.0	16.0		
				1.5			208	20.0	21.3	0.0	15.7		
				2.5			211	11.6	12.7	0.0	11.6		
				3.0			176	16.0	17.0	0.0	10.0		
				4.0			200	17.0	18.5	0.0	7.9		
				5.0			195	18.0	18.8	0.0	6.2		
				6.0			174	16.0	17.8	0.0	3.7		
				7.0		6.0	1 750	193	18.0	18.9	0.0		2.3
05/1/77	B2	14.0	4.1	0.0	7.5	3 650	160	13.0	16.0	0.2	8.6	0.027 4	
				0.5			150	13.0	14.3	0.1	7.0		
				1.0			150	13.0	14.5	0.1	5.1		
				1.5			160	13.0	15.7	0.0	2.6		
				2.0			160	13.0	14.8	0.0	0.7		
				3.0			130	13.0	15.6	0.0	0.0		
				4.0		8.0	3 610	120	13.0	16.3	0.0		0.0

Cont'd...../

TABLE B5 (CONT'D). PILOT PLANT BATCH DENITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Anoxic SRT ( $\theta_2$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g NO}_3\text{-N}}{\text{g MLVSS}\cdot\text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
11/7/76	C1	3.0	0.9	0.0	15.0	1 600	53	8.0	9.3	0.2	8.8	0.049 0
				0.5			45	8.0	8.2	0.1	8.7	
				1.0			46	8.0	8.7	0.1	6.5	
				1.5			44	8.0	8.0	0.2	8.1	
				2.0			44	8.0	8.1	0.1	2.6	
				2.5			38	7.0	7.0	0.2	2.1	
				3.0			16.0	1 430	48	7.0	8.2	
21/7/76	C1	3.5	1.0	0.0	15.0	1 810	122	7.0	8.7	2.4	15.8	
				0.5			114	6.0	7.7	1.4	13.6	
				1.0			111	5.0	6.9	0.7	10.7	
				1.5			92	3.0	4.6	0.1	5.0	
				2.0			100	4.0	4.7	0.1	5.9	
				2.5			45	6.0	7.7	1.6	4.6	
				3.0			95	5.0	6.0	0.1	5.8	
				4.0			119	8.0	8.9	0.4	5.5	
				5.0	16.5	1 900	110	7.0	7.9	0.3	5.4	
*0.071 4												

\* Rate calculation based on results up to 2.5 hr as carbon limitation occurred beyond this time.

Cont'd...../

TABLE B5 (CONT'D). PILOT PLANT BATCH DENITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Anoxic SRT ( $\theta_2$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g NO}_3\text{-N}}{\text{g MLVSS}\cdot\text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
13/8/76	C1	11.0	3.2	0.0	7.5	4 560	133	7.0	7.7	0.1	5.5	0.013 1
				0.5			150	6.0	7.2	0.1	5.4	
				1.0			139	7.0	7.6	0.1	3.7	
				1.5			116	4.0	6.8	0.1	2.0	
				2.0			82	4.3	5.0	0.1	0.9	
				2.5			97	5.8	5.8	0.1	0.1	
				3.0			123	7.2	7.2	0.0	0.0	
				4.0			135	7.5	7.6	0.0	0.0	
					9.0	4 300						
09/9/76	C1	1.0	0.3	0.0	14.5	900	123	10.0	10.7	0.1	13.2	
				0.5			131	9.0	11.0	0.2	13.0	
				1.0			107	9.0	11.6	0.3	12.3	
				1.5			118	9.8	11.5	0.4	11.5	
				2.0			120	10.0	11.3	0.4	11.8	
				2.5			119	9.0	11.8	0.4	10.6	
				3.0			112	9.0	11.2	0.4	9.6	
				4.0			97	10.0	10.8	0.4	7.8	
					15.0							0.033 6

Cont'd...../

TABLE B5 (CONT'D). PILOT PLANT BATCH DENITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Anoxic SRT ( $\theta_2$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g NO}_3\text{-N}}{\text{g MLVSS}\cdot\text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> -N	NO <sub>3</sub> -N	
22/9/76	C1	2.0	0.6	0.0	24.0	835	145	2.0	6.7	0.1	18.9	0.129 3
				0.5			153	5.0	7.0	0.8	18.5	
				1.0			146	4.0	6.7	1.0	15.6	
				1.5			118	5.0	6.6	3.9	14.6	
				2.0			129	6.0	6.6	4.2	13.5	
				2.5			107	6.0	6.1	4.9	6.6	
				3.0			95	5.0	5.9	4.2	2.9	
				4.0	22.0	910	92	5.0	5.4	0.0	0.3	
22/10/76	C1	4.0	1.2	0.0	25.0	1 730	112	3.0	3.0	0.6	12.2	
				0.5			100	2.0	2.6	1.7	7.5	
				1.0			80	2.0	2.5	3.2	1.9	
				1.5			64	2.0	2.8	2.1	0.0	
				2.0			70	2.0	2.8	0.0	0.0	
				2.5			67	2.0	2.9	0.0	0.0	
				3.0			62	3.0	3.0	0.0	0.0	
				4.0			66	3.0	3.1	0.0	0.0	
				5.0	25.0	1 440	62	3.0	3.0	0.0	0.0	
												0.099 1

Cont'd...../

TABLE B5 (CONT'D). PILOT PLANT BATCH DENITRIFICATION RESULTS

Date	Reactor	System SRT ( $\theta$ ) days	Anoxic SRT ( $\theta_2$ ) days	Batch Time hrs.	Temp. °C	MLVSS mg/L	Filtered Analyses, mg/L					Calculated Rate $\frac{\text{g NO}_3\text{-N}}{\text{g MLVSS}\cdot\text{day}}$
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	
26/11/76	C1	3.0	0.9	0.0	7.5	1 600	198	12.3	16.6	0.1	12.6	0.026 9
				0.5			204	12.5	15.8	0.1	12.6	
				1.0			197	12.5	16.4	0.1	11.2	
				1.5			203	12.5	16.5	0.1	9.8	
				2.0			179	12.8	16.5	0.1	10.3	
				2.5			187	13.4	17.1	0.1	9.8	
				3.0			194	13.0	17.6	0.1	7.6	
				4.0			186	13.0	17.6	0.1	5.6	
				5.0			180	12.6	14.0	0.1	4.0	
				6.0			190	13.5	16.4	0.1	2.7	
				7.0	8.0	1 430	188	13.6	17.9	0.1	1.1	
29/12/76	C1	16.0	4.3	0.0	7.0	3 780	115	16.0	17.6	0.1	13.0	0.022 7
				0.5			114	18.0	18.4	0.1	12.4	
				1.0			122	20.0	20.6	0.1	11.7	
				1.5			99	18.0	18.1	0.1	9.4	
				2.0			95	18.0	19.0	0.1	7.1	
				2.5			109	21.0	21.7	0.1	5.7	
				3.0			91	22.0	22.2	0.1	2.7	
				4.0			89	23.0	23.6	0.0	0.0	
				5.0			97	26.0	26.6	0.0	0.0	
				6.0			87	21.0	21.4	0.0	0.0	
				7.0	8.0	3 680	83	22.0	22.2	0.0	0.0	

### Denitrification Batch Experiments to Assess Methanol and Sewage as Carbon Sources and to Assess Rates Under Carbon and Non-Carbon Limiting Conditions

These batch experiments (Tables B6 and B7) were conducted outside of the pilot scale reactors using 12 L bench scale units. The reactors were jacketed, thereby allowing temperature control. They were rectangular in shape and were stirred slowly to keep the contents in suspension. The initial additions to the parallel reactors in each study are detailed in Tables B6 and B7.

### Organic Carbon Requirements for Denitrification in Single Sludge Systems

The calculations required to prepare Figures 19 and 20 appear in Table B8. To compare the C:N requirements for systems C or D and E, Figure 21 was prepared from the information presented in Table B9.

TABLE B6. BATCH STUDY TO ASSESS METHANOL AND SEWAGE AS CARBON SOURCES FOR DENITRIFICATION

Batch Reactor	Initial Reactor Additions	Batch Results									
		Time hrs.	Temp. °C	DO mg/L	pH	MLVSS mg/L	Filtered Analyses, mg/L				
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N
1	2.0 L of return sludge from system C operating at 7 to 8°C, a system SRT of 20 days, and an anoxic SRT of 6 days  8.5 L of sewage feed  1.15 g of NaNO <sub>3</sub>	0.0	5.5	0.0	6.9	2 600	141	23.0	27.2	0.3	19.3
		0.5					115	26.0	27.0	1.1	19.1
		1.0					115	26.0	26.8	1.5	16.7
		1.5	5.5	0.0			98	27.0	28.0	1.9	14.9
		2.0					87	28.0	28.8	2.3	13.3
		3.0					85	27.0	27.9	2.9	8.6
		4.0					71	25.0	26.0	3.3	4.7
		5.0	6.0		7.2	2 600	71	27.0	27.1	4.3	2.0
		6.0					78	22.0	22.6	3.3	0.0
2	3.5 L of return sludge from system C operating as above  7.0 L of tap water  1.1 mL of CH <sub>3</sub> OH  1.15 g of NaNO <sub>3</sub>	0.0	7.0	0.0	7.0	3 500	170	0.8	1.9	0.4	17.6
		0.5					165	0.9	2.0	0.0	17.8
		1.0					151	0.9	2.4	0.0	16.0
		1.5	7.0	0.0			117	0.9	2.9	0.0	13.7
		2.0					124	0.6	2.8	0.1	11.3
		3.0					133	0.6	3.0	0.0	7.8
		4.0					120	0.6	3.1	0.0	7.6
		5.0	7.0	0.0	7.2	3 570	112	0.6	1.0	0.0	1.3



TABLE B7. BATCH STUDY TO ASSESS RATE OF DENITRIFICATION UNDER CARBON AND NON-CARBON LIMITING CONDITIONS

Batch Reactor	Initial Reactor Additions	Batch Results									
		Time hrs.	Temp. °C	DO mg/L	pH	MLVSS mg/L	Filtered Analyses, mg/L				
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N
1	6.0 L of mixed liquor from reactor D1 of system D operating at a system SRT of 10 days and an anoxic SRT of 6 days  4.5 L of sewage feed  1.36 g of KNO <sub>3</sub>	0.0	16.0	0.2	7.2	1 470	45	9.0	10.1	0.2	15.6
		0.5	-	-			45	9.0	10.1	0.1	15.3
		1.0					28	11.0	11.3	0.2	15.0
		2.0					33	10.0	10.6	0.2	9.8
		3.0	15.0	0.2			33	10.0	10.8	0.2	7.1
		4.0					37	11.0	11.5	0.2	4.5
		5.0	15.0	0.3	7.4		37	10.0	10.5	0.0	0.0
		6.0	15.0	0.1	7.5	1 440	28	9.0	10.7	0.0	0.0
2	6.0 L of mixed liquor from reactor D1 of system D operating as above  2.25 L of sewage feed  2.25 L of tap water  1.36 g of KNO <sub>3</sub>	0.0	15.5	0.2	7.2	1 280	24	4.0	5.7	0.2	18.3
		0.5					24	5.0	5.9	0.3	17.8
		1.0					28	5.0	6.6	0.3	15.8
		2.0					16	6.0	6.8	0.2	12.1
		3.0	15.5	0.3			20	6.0	7.0	0.2	10.2
		4.0					16	5.8	6.2	0.3	8.2
		5.0	15.0	0.2	7.4		16	5.9	8.2	0.3	6.8
		6.0					20	5.8	6.8	0.3	4.9
		7.0					24	5.8	6.0	0.4	3.5
		8.0	15.0	0.1	7.5		20	5.8	6.6	0.4	2.0
		9.0	15.0	0.2	7.5	1 380	24	5.8	7.7	0.3	0.9

Cont'd...../

TABLE B7 (CONT'D). BATCH STUDY TO ASSESS RATE OF DENITRIFICATION UNDER CARBON AND NON-CARBON LIMITING CONDITIONS

Batch Reactor	Initial Reactor Additions	Batch Results									
		Time hrs.	Temp. °C	DO mg/L	pH	MLVSS mg/L	Filtered Analyses, mg/L				
							COD	NH <sub>3</sub> -N	TKN	NO <sub>2</sub> <sup>-</sup> -N	NO <sub>3</sub> <sup>-</sup> -N
3	6.0 L of mixed liquor from reactor D1 of system D operating as above  4.5 L of tap water  1.36 g of KNO <sub>3</sub>	0.0	15.5	2.0	7.2	1 280	16	1.3	2.3	0.3	17.7
		0.5		0.3			24	1.2	2.5	0.3	17.6
		1.0					24	1.1	2.2	0.2	16.3
		2.0					12	1.2	2.2	0.1	15.6
		3.0	15.0	0.3			20	1.1	2.2	0.2	14.0
		4.0					24	1.1	1.9	0.2	12.8
		5.0	15.0	0.2	7.3		20	1.2	2.1	0.2	11.5
		6.0					24	1.0	2.2	0.2	9.2
		7.0					20	1.0	1.9	0.2	9.2
		8.0	15.0	0.1	7.5		24	1.0	1.7	0.2	7.9
		9.0					45	1.0	1.7	0.2	7.0
		10.0					24	1.0	2.1	0.1	6.1
		11.0					24	1.0	1.8	0.1	4.9
		12.0					20	1.0	1.9	0.1	4.1
		13.0	15.0	0.2	7.6	1 280	20	1.0	1.8	0.1	3.1

TABLE B8. COD UTILIZATION IN PRE AND POST-DENITRIFICATION SYSTEMS

Run No.	System	Temp. °C	Anoxic SRT	Feed Unfiltered TKN $\text{mg}\cdot\text{L}^{-1}$	Unfiltered Feed COD Plus $\text{CH}_3\text{OH}$ as COD $\text{mg}\cdot\text{L}^{-1}$ of feed	*Filtered Feed COD Available Plus $\text{CH}_3\text{OH}$ as COD $\text{mg}\cdot\text{L}^{-1}$ of flow	**Anoxic Reactor Equivalent $\text{NO}_3^-$ -N Reduced $\text{mg}\cdot\text{L}^{-1}$ of flow	Anoxic Reactor $\text{NO}_3^-$ -N+ $\text{NO}_2^-$ -N $\text{mg}\cdot\text{L}^{-1}$	Filterable COD Available Equivalent $\text{NO}_3^-$ -N Reduced	†Unfiltered Feed COD Plus $\text{CH}_3\text{OH}$ as COD Unfiltered Feed TKN
41	C	7-8	6-7	18.8	372	40.2	1.80	0.4	22.3	19.8
42	C	7-8	6-7	23.4	382	43.0	3.30	0.4	13.0	16.3
44	C	7-8	6-7	34.3	500	36.8	2.97	0.2	12.4	
45	C	7-8	6-7	29.2	450	27.0	2.68	0.4	10.1	15.4
46	C	7-8	6-7	27.0	390	27.0	2.87	0.2	9.4	14.4
47	D	7-8	6-7	19.6	230	15.6	3.35	3.9	4.7	11.7
48	D	7-8	6-7	24.5	280	15.5	4.42	2.4	3.5	
49	D	7-8	6-7	22.9	260	20.4	4.15	2.8	4.9	11.3
1	D	14-16	1-2	22.2	298	13.0	4.09	6.1	3.2	13.4
2	D	14-16	1-2	19.0	306	13.0	5.08	3.5	2.6	
50	D	14-16	1-2	21.3	240	16.2	5.56	7.8	2.9	11.3
51	D	14-16	1-2	20.3	220	15.8	7.33	8.8	2.2	10.8
52	C	14-16	1-2	19.9	280	19.6	4.33	1.9	4.5	14.1
53	C	14-16	1-2	23.2	300	24.4	3.60	0.1	6.8	12.9
55	C	24-26	1	19.8	352	27.2	2.31	0.2	11.8	17.8
56	C	24-26	1	25.3	342	30.2	1.92	0.9	15.7	13.5
57	D	24-26	1	31.5	330	14.8	2.65	4.9	5.6	10.5
58	D	24-26	1	31.6	368	18.8	2.71	2.9	6.9	11.6
59	C	24-26	1	35.4	500	35.2	2.78	0.1	12.7	14.1
13	B	7-8	3-7			77.5	7.4	0.4	10.5	
14	B	7-8	3-7			77.5	7.0	0.2	11.1	
15	B	7-8	3-7			77.5	6.6	0.8	11.8	
16	B	7-8	3-7			77.5	4.7	0.1	16.5	
17	B	7-8	3-7			77.5	3.4	2.3	22.8	
34	B	7-8	3-7			77.5	3.1	0.0	25.0	

\* For system B, the value here is equal to methanol fed to anoxic reactor.

\*\* This calculation includes dissolved oxygen reduced in anoxic reactor.

† Calculated only when effluent ammonia-N less than or equal to  $2.0 \text{ mg}\cdot\text{L}^{-1}$ .

Cont'd...../

TABLE B8 (CONT'D). COD UTILIZATION IN PRE AND POST-DENITRIFICATION SYSTEMS

Run No.	System	Temp. °C	Anoxic SRT	Feed Unfiltered TKN $\text{mg}\cdot\text{L}^{-1}$	Unfiltered Feed COD Plus $\text{CH}_3\text{OH}$ as COD $\text{mg}\cdot\text{L}^{-1}$ of feed	*Filtered Feed COD Available Plus $\text{CH}_3\text{OH}$ as COD $\text{mg}\cdot\text{L}^{-1}$ of flow	**Anoxic Reactor Equivalent $\text{NO}_3^-$ -N Reduced $\text{mg}\cdot\text{L}^{-1}$ of flow	Anoxic Reactor $\text{NO}_3^-$ -N+ $\text{NO}_2^-$ -N $\text{mg}\cdot\text{L}^{-1}$	Filterable COD Available Equivalent $\text{NO}_3^-$ -N Reduced	† Unfiltered Feed COD Plus $\text{CH}_3\text{OH}$ as COD Unfiltered Feed TKN
35	B	7-8	3-7			77.5	3.2	0.1	24.2	
36	B	7-8	3-7			77.5	2.7	0.0	28.7	
39	B	7-8	3-7			60.5	4.5	0.2	13.4	
41	B	7-8	3-7			60.5	6.6	0.3	9.2	
42	B	7-8	3-7			60.5	7.6	0.0	8.0	
43	B	7-8	3-7			60.5	6.9	0.8	8.8	
44	B	7-8	3-7			30.5	9.7	0.6	3.1	
45	B	7-8	3-7			30.5	7.4	1.2	4.1	

\* For system B, the value here is equal to methanol fed to anoxic reactor.

\*\* This calculation includes dissolved oxygen reduced in anoxic reactor.

† Calculated only when effluent ammonia-N less than or equal to  $2.0 \text{ mg}\cdot\text{L}^{-1}$ .

TABLE B9. COMPARISON OF INFLUENT C:N ON DENITRIFICATION IN PRE-DENITRIFICATION SYSTEMS (C OR D) AND IN STEP-FEED SYSTEM (E)

Run No.	System	Feed Unfiltered TKN $\text{mg} \cdot \text{L}^{-1}$	Feed Unfiltered COD Plus $\text{CH}_3\text{OH}$ as COD $\text{mg} \cdot \text{L}^{-1}$	Feed Unfiltered COD Plus $\text{CH}_3\text{OH}$ as COD Feed Unfiltered TKN	System Effluent $\text{NO}_2^- - \text{N}$ Plus $\text{NO}_3^- - \text{N}$ $\text{mg} \cdot \text{L}^{-1}$
1	D	22.2	298	13.4	11.4
5	C	27.3	590	21.6	0.6
6	C	21.5	554	25.8	2.0
50	D	21.3	240	11.3	15.1
51	D	20.3	220	10.8	18.5
52	C	19.9	280	14.1	6.4
53	C	23.2	300	12.9	3.7
51	E	20.3	220	10.8	14.3
52	E	19.9	210	10.6	12.3
53	E	23.2	230	9.9	12.3
66	E	28.1	360	12.8	2.5
67	E	32.7	350	10.7	4.1
68	E	27.9	390	14.0	1.9

## APPENDIX C

### Abbreviations and Symbols

## APPENDIX C

### Abbreviations and Symbols

Abbreviations and symbols appearing in this report not commonly used are listed below:

$\theta$	-	system SRT (days)
$\theta'$	-	constant, in modified Arrhenius model
$\theta_1$	-	aerobic SRT (days)
$\theta_{1c}$	-	critical aerobic SRT (days)
$\theta_2$	-	anoxic SRT (days)
$\theta_{2c}$	-	critical anoxic SRT (days)
$A$	-	frequency factor in Arrhenius model ( $\text{day}^{-1}$ )
$\text{BOD}_5$	-	five-day biochemical oxygen demand ( $\text{mg}\cdot\text{L}^{-1}$ )
$\text{C}_a\text{H}_b\text{O}_c$	-	form of carbon substrate
$\text{CaCO}_3$	-	calcium carbonate
$\text{CH}_3\text{OH}$	-	methanol
$\text{COD}$	-	chemical oxygen demand ( $\text{mg}\cdot\text{L}^{-1}$ )
$\bar{D}$	-	statistical mean difference between observed and predicted values
$\text{DO}$	-	dissolved oxygen ( $\text{mg}\cdot\text{L}^{-1}$ )
$E$	-	activation energy ( $\text{cal}\cdot\text{g-mole}^{-1}$ )
$\text{HRT}$	-	hydraulic retention time
$K_{15}$	-	reaction rate constant at $15^\circ\text{C}$ ( $\text{day}^{-1}$ )
$K_A$	-	ammonia oxidation rate ( $\text{mg}\cdot\text{mg}^{-1}\cdot\text{day}^{-1}$ )
$K_A^*$	-	maximum ammonia oxidation rate ( $\text{mg}\cdot\text{mg}^{-1}\cdot\text{day}^{-1}$ )
$K_{AV}^*$	-	maximum ammonia oxidation rate based on total volatile suspended solids ( $\text{mg}\cdot\text{mg}^{-1}\cdot\text{day}^{-1}$ )

$K_N$	-	denitrification rate ( $\text{mg} \cdot \text{mg}^{-1} \cdot \text{day}^{-1}$ )
$K_N^*$	-	maximum denitrification rate ( $\text{mg} \cdot \text{mg}^{-1} \cdot \text{day}^{-1}$ )
$K_{NE}$	-	endogenous denitrification rate ( $\text{mg} \cdot \text{mg}^{-1} \cdot \text{day}^{-1}$ )
$K_{NV}^*$	-	denitrification rate based on total volatile suspended solids ( $\text{mg} \cdot \text{mg}^{-1} \cdot \text{day}^{-1}$ )
$\text{KNO}_3$	-	potassium nitrate
$K_T$	-	reaction rate constant at temperature T ( $\text{day}^{-1}$ )
$K_{T'}$	-	reaction rate constant at temperature T' ( $\text{day}^{-1}$ )
mg	-	milligram
MLVSS	-	mixed liquor volatile suspended solids ( $\text{mg} \cdot \text{L}^{-1}$ )
N	-	nitrogen ( $\text{mg} \cdot \text{L}^{-1}$ )
NS	-	autotrophic bacteria of the genera nitrosomonas
$\text{NaNO}_3$	-	sodium nitrate
$\text{NH}_3\text{-N}$	-	ammonia nitrogen ( $\text{mg} \cdot \text{L}^{-1}$ )
$\text{NH}_4^+\text{-N}$	-	ammonia plus ammonium-nitrogen ( $\text{mg} \cdot \text{L}^{-1}$ )
$\text{NH}_4\text{-Cl}$	-	ammonium chloride
$\text{NO}_2^-\text{-N}$	-	nitrite nitrogen ( $\text{mg} \cdot \text{L}^{-1}$ )
$\text{NO}_3^-\text{-N}$	-	nitrate nitrogen ( $\text{mg} \cdot \text{L}^{-1}$ )
R	-	filterable TKN removed ( $\text{mg} \cdot \text{L}^{-1}$ )
$R_1$	-	filterable TKN assimilated ( $\text{mg} \cdot \text{L}^{-1}$ )
$\frac{R_1}{C_o}$	-	fraction of filterable TKN assimilated
$\frac{R'}{C_o'}$	-	total fraction of filterable TKN removed
$\frac{R}{C_o}$	-	fraction of filterable available TKN for nitrification, removed



Reactor Identification (refer to Figure 1):

A1 - first stage (carbon oxidation-nitrification) of system A.

A2 - second stage (denitrification) of system A.

B1 - first stage (carbon oxidation-nitrification) of system B.

B2 - second stage (denitrification) of system B.

C1 - first stage (denitrification) of system C.

C2 - second stage (nitrification) of system C.

D1 - first stage (denitrification) of system D.

D2 - second stage (nitrification) of system D.

E1 - first stage (denitrification) of system E.

E2 - second stage (nitrification) of system E.

E3 - third stage (denitrification) of system E.

E4 - fourth stage (nitrification) of system E.

E5 - fifth stage (denitrification) of system E.

E6 - sixth stage (nitrification) of system E.

SRT - system solids retention time (days)

SS - suspended solids ( $\text{mg}\cdot\text{L}^{-1}$ )

System Identification (refer to Figure 1):

A - System A. Carbon oxidation-nitrification followed by post-denitrification with no external carbon source addition.

B - System B. Carbon oxidation-nitrification followed by post-denitrification with external carbon source addition.

- C - System C. Pre-denitrification followed by nitrification with external carbon source addition.
- D - System D. Pre-denitrification followed by nitrification with no external carbon source addition.
- E - System E. Step-feed nitrification denitrification.

TKN	-	total Kjeldahl nitrogen ( $\text{mg} \cdot \text{L}^{-1}$ )
TP	-	total phosphorus ( $\text{mg} \cdot \text{L}^{-1}$ )
U	-	growth rate of all organisms in an activated sludge system ( $\text{days}^{-1}$ )
$U_{\text{DN}}$	-	growth rate of denitrifiers ( $\text{days}^{-1}$ )
$U_{\text{NS}}^*$	-	maximum nitrifier growth rate ( $\text{days}^{-1}$ )
$U_{\text{NS}}$	-	growth rate of NS ( $\text{days}^{-1}$ )
VSS	-	volatile suspended solids ( $\text{mg} \cdot \text{L}^{-1}$ )
X	-	active total volatile suspended solids ( $\text{mg} \cdot \text{L}^{-1}$ )
$X_{\text{DN}}$	-	denitrifier mixed liquor volatile suspended solids concentration ( $\text{mg} \cdot \text{L}^{-1}$ )
$X_{\text{NS}}$	-	NS mixed liquor volatile suspended solids concentration ( $\text{mg} \cdot \text{L}^{-1}$ )
Y	-	organism system yield coefficient ( $\text{mg} \cdot \text{mg}^{-1}$ )
$Y_{\text{H}}$	-	heterotroph yield coefficient ( $\text{mg} \cdot \text{mg}^{-1}$ )
$Y_{\text{NS}}$	-	actual yield coefficient ( $\text{mg} \cdot \text{mg}^{-1}$ ) for nitrifiers
$Y'_{\text{NS}}$	-	net yield coefficient ( $\text{mg} \cdot \text{mg}^{-1}$ ) for nitrifiers

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